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DEVONIAN SEDIMENTS OF EAST GREENLAND IV

THE WESTERN SEQUENCE, KAP KOLTHOFF SUPERGROUP OF THE WESTERN AREAS

BY

A. K. YEATS AND P. F. FRIEND

WITH 72 FIGURES AND 11 TABLES

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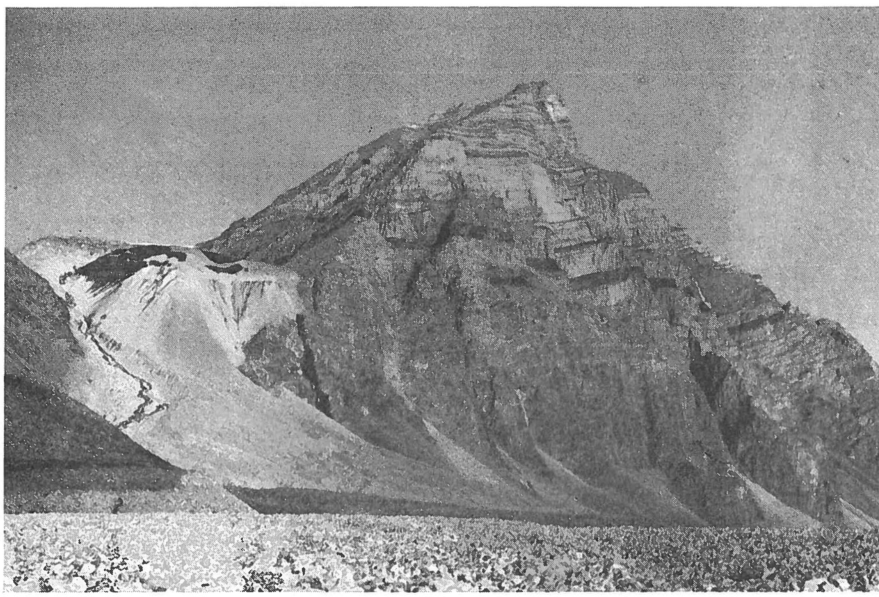

The southern part of the western margin of the East Greenland Devonian sediment area, is formed by a spectacular wall of sediment overlooking Kong Oscars Fjord. This photograph taken on the delta of 'valley e', looks southwards to the point labelled as 1306 (m) high on South Kongeborgen, on the 1/250,000 Geodetisk Institut map. The wall of the mountain consists of Kap Kolthoff Supergroup sandstones, showing banding due to the presence of megacycles. The face is intruded by dark sills of Cretaceous-Tertiary age.

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BIANCO LUNOS BOGTRYKKERI A/S

Abstract

A 2 km succession of upper Middle and Upper Devonian fluvial conglomerates and sandstones outcrops along a north-south distance of 160 km, and forms the western sequence of the Devonian outcrop area of East Greenland.

The thickness of the conglomerates varies considerably along the western margin, and this appears to represent the growth of distinct coarse grained fans. These coarse fluvial deposits range up to 1000 m in thickness. Breccias are locally present on the basal unconformity, sometimes including clasts up to 15 m long, that appear to have slipped and rolled from nearby outcrops of basement (pre-Devonian) sediment. Although some of the breccias were certainly deposited from water, others may have accumulated from debris flows. A number of ravines and valleys eroded in the basement, are preserved with plugs of breccia or conglomerate. Thin limestone and siltstone units occur, also close to the unconformity, and are thought to have formed in lake hollows between the highgradient alluvial deposits and the basement topography.

Most of the outcrops of the area are of rather similar sandstone sequences. These have been analysed, particularly using our multivariate analytical technique, described in number 1 of this volume. Palaeocurrents and lithology show the presence of a number of distinct sandstone bodies, hundreds of metres thick, and kilometres in lateral extent. These distinctive bodies were deposited by broadly eastward flowing river fan systems at the margin of the Devonian outcrop area. A southward flowing (axial) river system deposited sands further east, in the centre of the basin. The fan sandstone bodies are characterised by cycles, 20 to 100 m thick. In the central parts of the fans, these cycles consist of an upwards increase in the proportion of flat-bedding to cross-bedding, although the medium sand grade is relatively constant. The edges of the fan bodies are marked by very-fine sand grade accumulations, interpreted as the fills of hollows between fans, or between a fan and the basement topography. Five of these fan sandstone bodies are green, and one is red and we suggest that this reflects different hydrological conditions.

A. K. Yeats
Shell International Company
Carel van Bylandtlaan 30
Den Haag
The Netherlands

P. F. Friend
University of Cambridge
Sedgwick Museum
Downing Street
Cambridge CB2 3EQ
England

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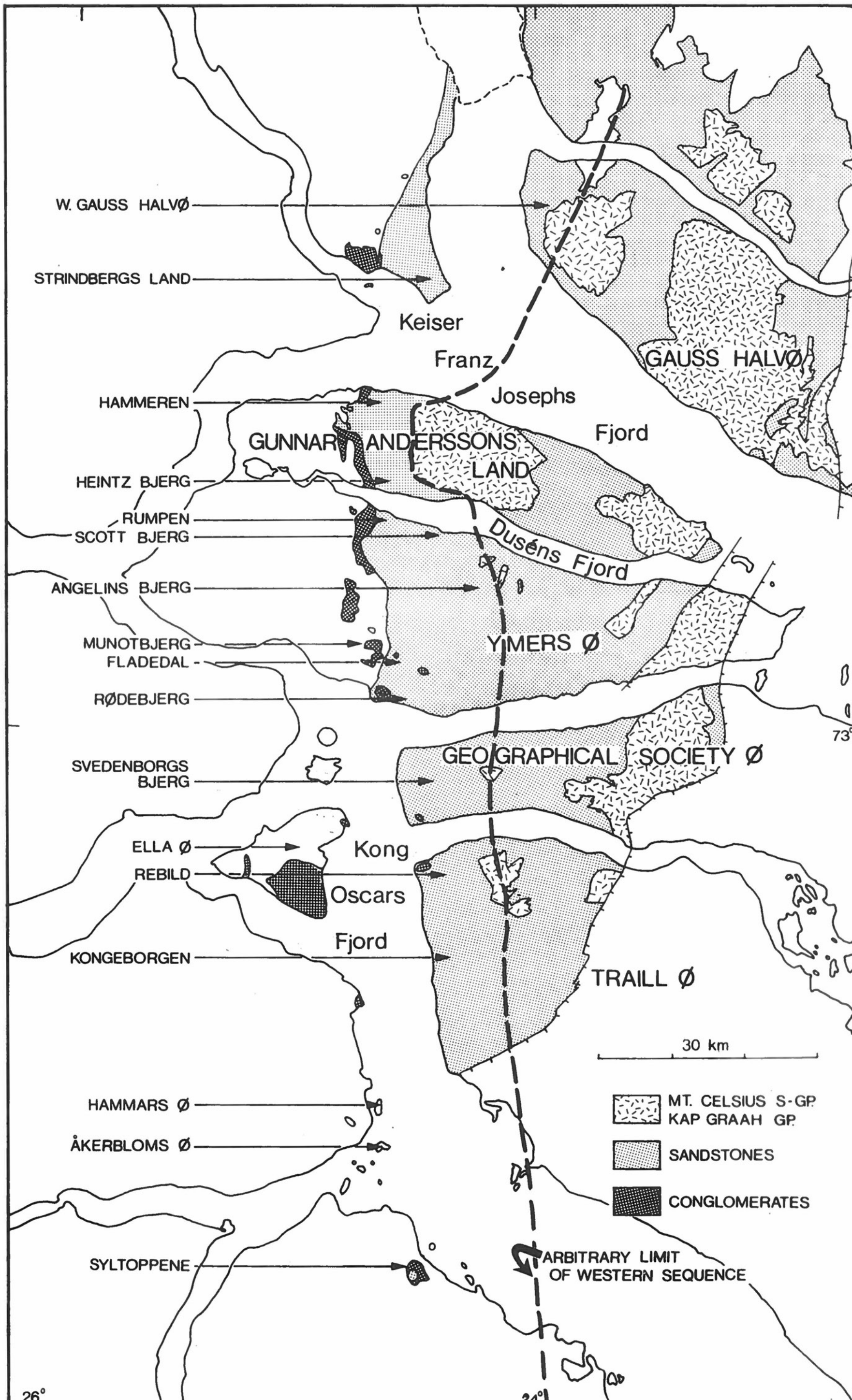

Fig. 1. Map of main Devonian outcrop area in East Greenland. The arbitrary limit of the western sequence of Devonian rocks is shown. The most important locality names are shown.

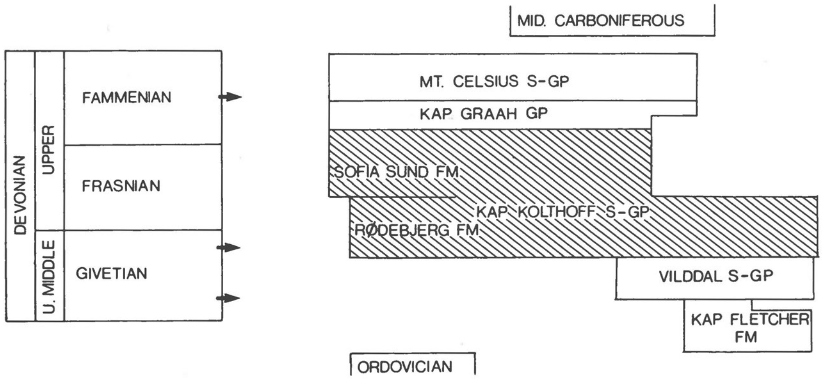

Fig. 2. The main lithostratigraphical units of the East Greenland Devonian succession. Approximate ages of the units are indicated, with arrows showing the actual age determinations.

INTRODUCTION

A thick succession of sandstones and conglomerates forms the western margin of the area of Devonian outcrops in East Greenland (Fig. 1). It is this succession that forms the subject of this paper. All the sediments are assigned by us to our Kap Kolthoff Supergroup (Fig. 2), and they appear to range in age from Givetian (upper Middle Devonian) to Fammenian (upper Upper Devonian).

This paper is based on field work carried out in the summers of 1968, 1969 and 1970 by members of the Cambridge Greenland Expeditions (Friend, 1969, 1970, 1971). These expeditions, and the general features of the Devonian sediments of East Greenland, have been described by Friend, Alexander-Marrack, Nicholson & Yeats, in the earlier numbers of this volume of *Meddelelser om Grønland.*

In Number 1, we have explained our use of a classification system for standard (generally 10 m, sometimes 5 m) intervals of our sedimentary logs. This classification is used throughout the present paper. A list and examples of the classes are presented here (Fig. 3, 4, 5, 6). We usually refer to the classes using a label, consisting of a number and letter (eg. 2A) and a short description (eg. red-m.,f.sst.-trough X,flat). This short description means (i) predominant colour, red, (ii) greatest proportion of interval (10 m or 5 m) is medium sandstone grade, next most abundant sediment is fine sandstone grade, (iii) predominant internal structure is trough cross-bedding, next commonest is flat bedding.

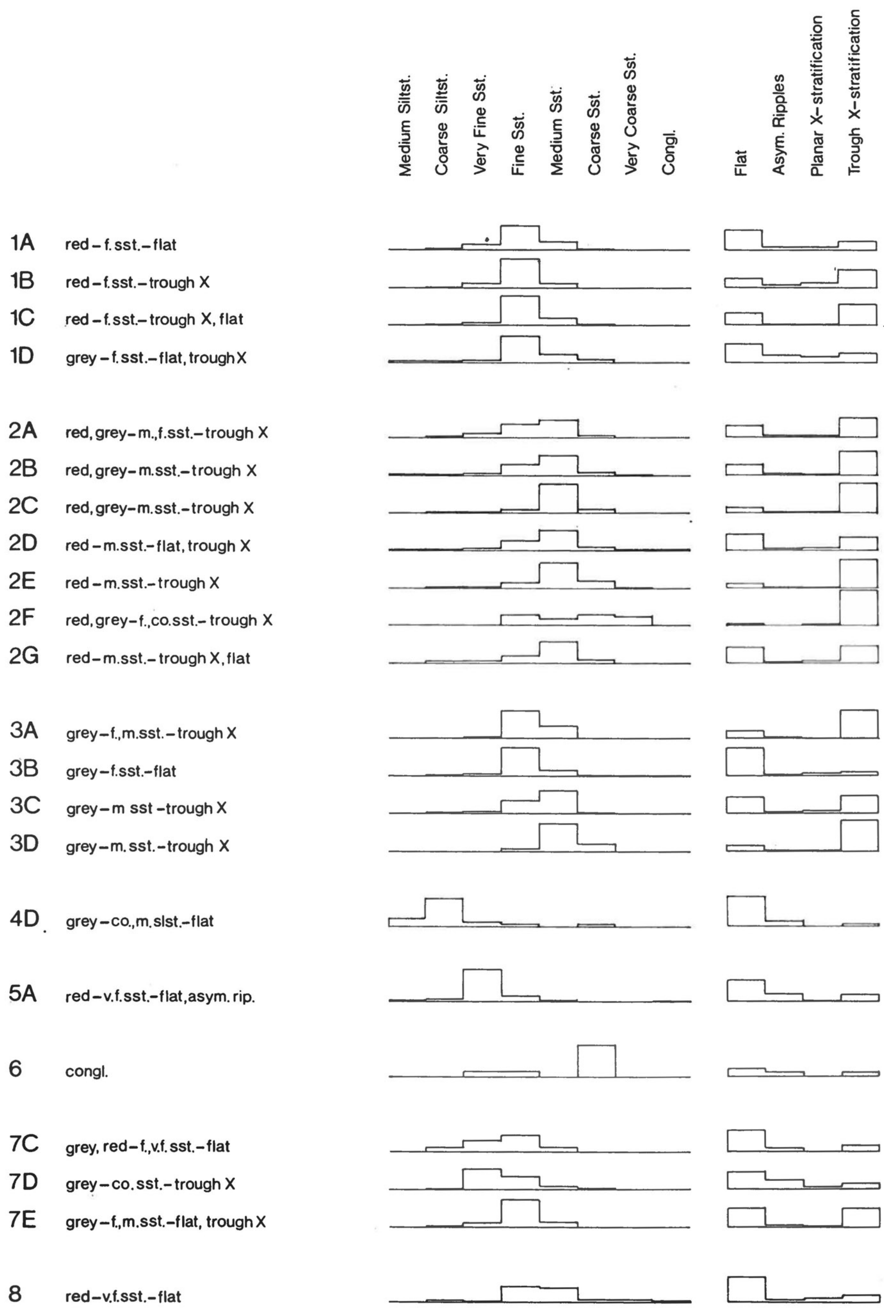

Fig. 3. Summary of sample groups resulting from classification of standard length units of sedimentary logs. Brief standard descriptions, and average proportions of thicknesses of different grain-sizes and different internal structures are given.

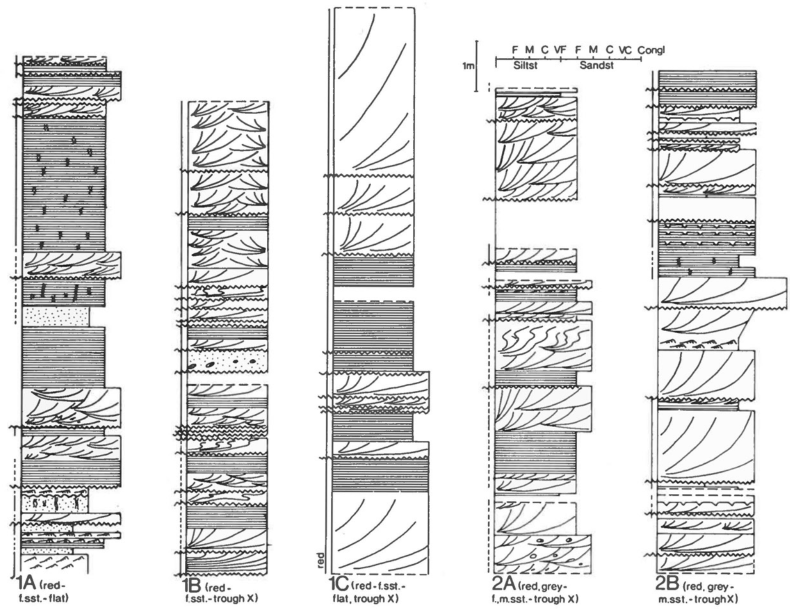

Fig. 4. Typical examples of 10 m. samples from various sample groups. Symbols explained in Fig. 6.

In Number 2 of this volume of *Meddelelser om Grønland* we have provided details of the sedimentary structures and fossils.

We shall follow this Introduction with a systematic review of the stratigraphy and structure of the western margin. Then we shall present detailed analyses of the environments of deposition, first of the conglomerates, and then of the sandstones.

STRATIGRAPHY AND STRUCTURE OF THE WESTERN MARGIN

Biostratigraphy

Outcrops of the western sequence have yielded few fossils compared with those of the central and eastern sequences. So few are the fossils that they are of almost no value in correlation between the various mountain areas of the western sequence.

The following is a list of fossil localities (north to south, see Fig. 1), based on a brief survey of the literature, and our own discoveries.

1) *Western Gauss Halvø* Kulling (1931, p. 13) reported plant remains from the "lower grey sandstone", which we think to be the Kap Kolthoff Supergroup.

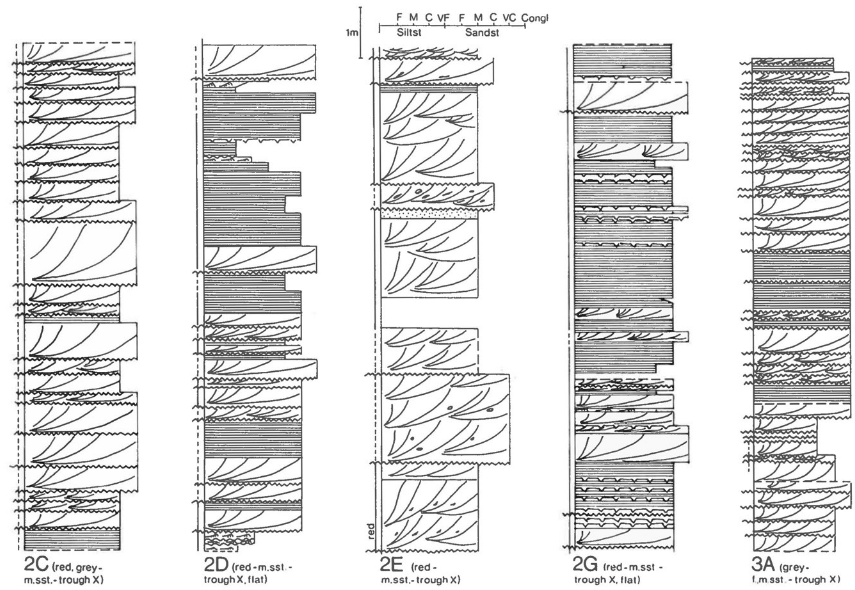

Fig. 5. Typical examples of 10 m samples from various sample groups. Symbols explained in Fig. 6.

2) "*Mt. Botriolepis*" (mountain east of Hammeren). STENSIÖ (1948, fig. 272, locality 7; p. 601, locality C) reported *Bothriolepis jarviki.*

3) *Eastern Heintz Bjerg* (West of Zoologdalen). STENSIÖ (1948, fig. 272, locality 9; p. 601, locality E) reported *Bothriolepis jarviki* from a number of localities in grey-green rocks, assumed by us to be Kap Kolthoff Supergroup.

4) *Blaskbjerg* (Northern Duséns Fjord). STENSIÖ (1948, fig. 272, locality 8; p. 601, locality D) reported *Bothriolepis jarviki.*

5) *Rødebjerg.* STENSIÖ (1931, fig. 1, locality 10) and KULLING (1931, p. 13) reported indeterminate vertebrate fragments. We found Crossopterygian scales and head fragments (one submitted to Dr. JARVIK).

6) *Ella Ø*, undoubtedly our most interesting find. Rich vertebrate and plant assemblage from limestones and siltstones, low in the succession, north of the outlier.
Vertebrates: *Glyptolepis* and *Asterolepis* (R. S. MILES, personal communication).
Plants: *Svalbardia*, *Pseudosporochnus* and rich microflora (K. C. ALLEN, personal communication; suggests Givetian age).

7) *Kongeborgen.* STENSIÖ (1931, fig. 1, locality 11; 1948, p. 601, locality F) reported *Bothriolepis jarviki.*

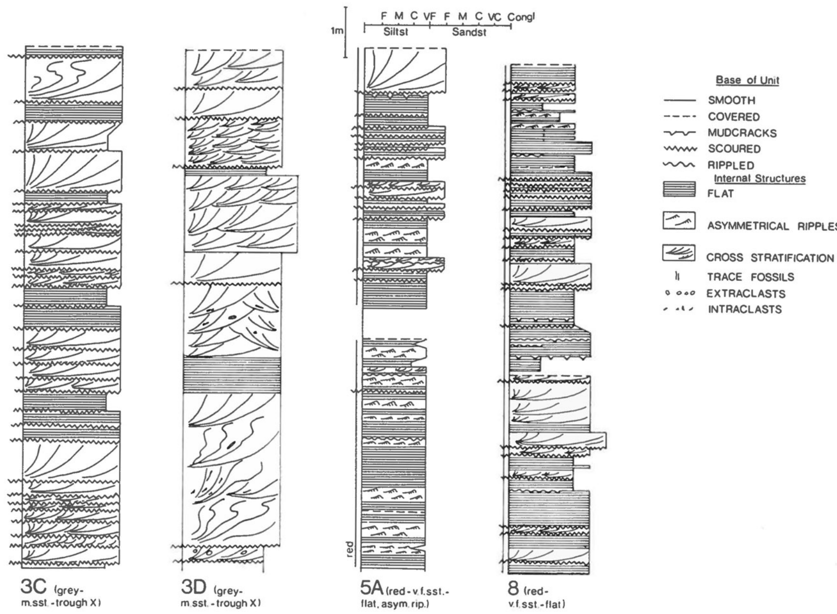

Fig. 6. Typical examples of 10 m samples from various sample groups.

8) *Åkerbloms Ø.* STENSIÖ (1931, fig. 1, locality 1) and KULLING (1931, p. 5) reported the fossils to be indeterminate.

The *Bothriolepis jarviki* fauna has been regarded as early Fammenian (JARVIK, 1961, p. 198). Apart from this, biostratigraphers have been able to do little in the way of dating the earlier part of their "Lower Sandstone Complex" (JARVIK, 1961, p. 198). Out discoveries on Ella Ø suggest that the lowest part of the succession in the west is Givetian. Because we find no major stratigraphic break within the Kap Kolthoff Supergroup of the western margin, deposits of Frasnian age must also be present, although there is not yet any positive faunal evidence for this.

Lithostratigraphy

Because of the absence of any local biostratigraphy, our reconstruction of the larger sedimentary environments has been based on lithostratigraphic correlation. Our lithostratigraphic analysis of the ten main areas will be discussed below, starting in the north. In Table 11, we review our formal stratigraphic terminology.

Strindbergs Land

The Devonian outcrops of the southeast of Strindbergs Land are remarkable for their uniformity east of the immediate area of the boundary fault. At Kap Ovibos (Fig. 7) in the extreme east, outcrops of grey-

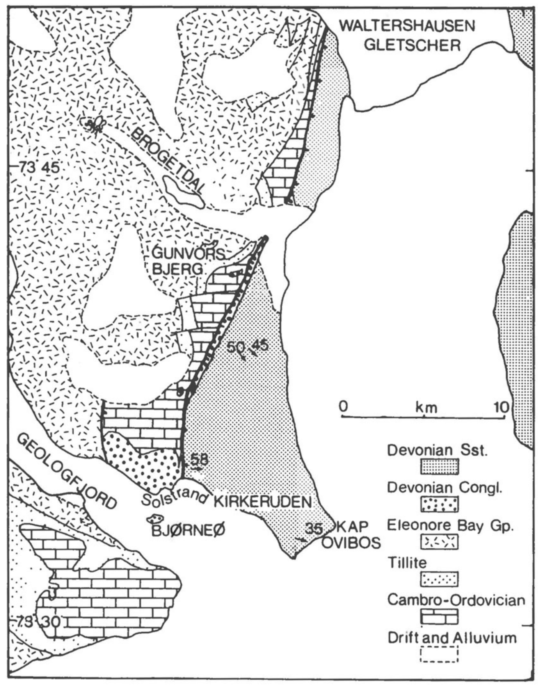

Fig. 7. Outline geological map of Strindbergs Land (based largely on Koch & Haller, 1971).

green sandstones dip at 35° to 45° to the east-southeast and east, and form the highest parts of a monocline that extends, with the same lithology and similar dip for a distance up dip of 8 km.

In some localities within half a kilometre of the boundary fault, the strata dip at higher angles. In Brogetdal, to the north, a 100 m wide vertically-dipping sheet of conglomerate has been faulted against Eleonore Bay Group outcrops. In contrast, the summit of Gunvors Bjerg, half a kilometre west of this fault is composed of a thin sheet of Devonian conglomerates, sandstones and siltstone that dips gently (about 20°) to the south, and rests unconformably on the Eleonore Bay Group limestones.

On the south shore of Strindbergs Land, along Geologfjord, the boundary fault region consists of a number of fault blocks. A small valley extends northwards from the east end of Solstrand and exposes the transition from the main sandstone monocline down into a sequence of interbedded conglomerates and sandstones. This sequence is faulted against a major area of conglomerate outcrops, again dipping at about 45° to the southeast. At the western end of Solstrand is another fault that divides the steep conglomerates from gently dipping conglomerates, up

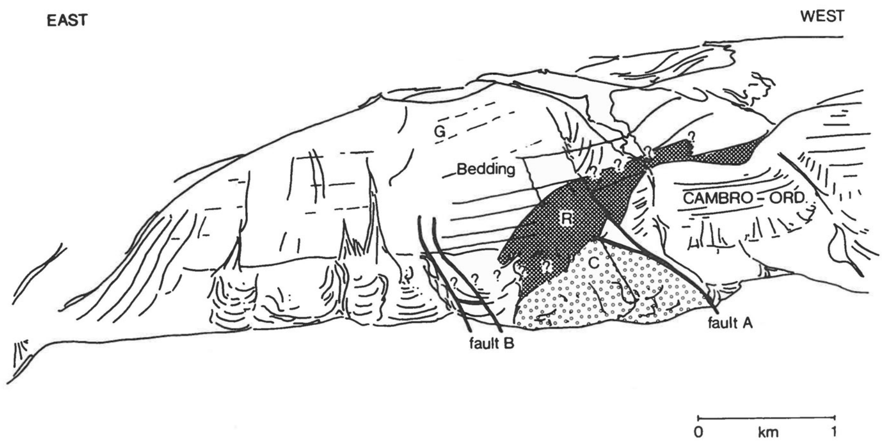

Fig. 8. Sketch of north face of Hammeren, Gunnar Andersens Land, showing main geological features. A, B, faults. G, green sandstone. R, red sandstone. Rings, conglomerate. R–G, red and green sandstones. C, conglomerate.

to 800 m in thickness, forming major cliffs above Geologfjord and the island Bjørneø, in mid fjord.

We summarise the succession (at least 6520 m) in Strindbergs Land as follows:

top of succession
greater than 5000 m, grey-green sandstone
300 m red and green banded sandstone
300 m green sandstone
120 m red sandstone with conglomerate (in distinct sheets averaging 20 m thick)
800 m conglomerate (at least)
base of outcrops

This succession agrees well with that described by BÜTLER (1948, p. 114, 116). Some structures in this area were discussed by KATZ (1952, p. 143).

Hammeren

This steep, northward-facing wall, overlooking Kejser Franz Josephs Fjord (Fig. 1) provides a section through the western edge of the basin (Fig. 8). The basal Devonian unconformity dips eastward at an average angle of 20°. The nature of the sub-Devonian unconformity is described in greater detail in a later part of this paper. A fault (A) (Fig. 8) with 300–400 m eastward downthrow cuts the unconformity 1 km west of the place (B) where it dips below fjord level and two smaller faults locally bring up the Pre-Devonian rocks to the surface again (Fig. 8). Bedding dip in the Devonian reaches a maximum of 20° to the east, near the unconformity.

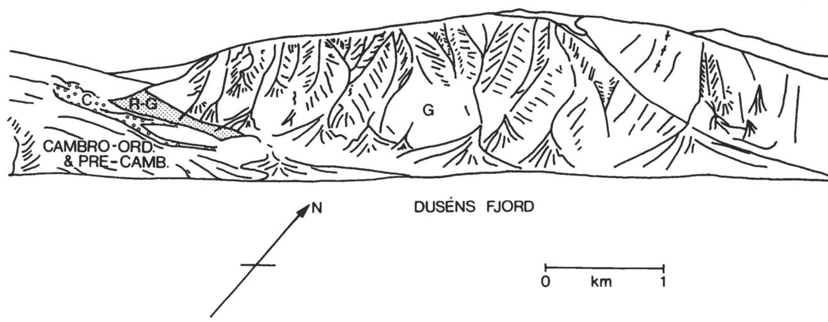

Fig. 9. Sketch of south face of Heintz Bjerg, Gunnar Andersens Land, showing main geological features. Key in Fig. 8.

The Devonian strata overlap, to some extent, against the unconformity.

The following succession (1600 m) can be given in summary:

top of succession
4) 600 m red and green sandstone
3) 800 m green sandstone
2) 50–100 m red sandstone, apparently passing laterally into 3
1) 100 m conglomerate
unconformity
Cambro-Ordovician strata

BÜTLER (1948, p. 117) reported 2500–3000 m of green sandstone above 100 m of conglomerate, and we suggest that this was based on a generalisation of the succession from Hammeren along the coast for at least 20 km to the east.

Heintz Bjerg

This is the name given by us to a mountain (Fig. 1) that overlooks Dusēns Fjord from the north (Fig. 9). Generally unfolded Devonian strata overlie Cambro-Ordovician limestones that form the lower ground to the south-west of the mountain.

We found a number of small faults along the outcrop of the unconformity. These are all normal faults, and their strikes vary from northerly, north-easterly and easterly. There is distinct evidence that these faults formed topographic scarps at the time of the first Devonian sedimentation. There is also evidence for movement along some surfaces that caused local folding after the lithification of the Devonian sediments. There are other small faults within the Devonian sediments, some hundreds of metres from the unconformity.

The succession (1600 m +) on Heintz Bjerg is as follows:

top of succession
4) thickness unknown, red sandstone

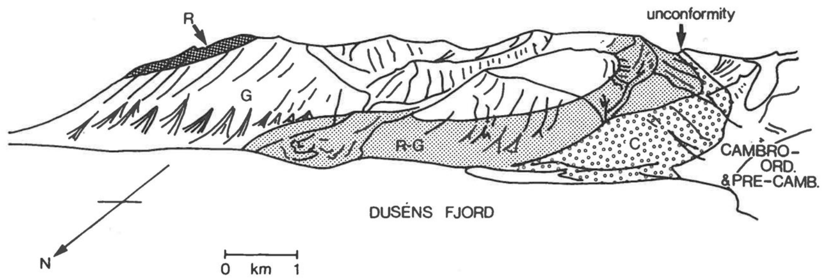

Fig. 10. Sketch of north face of Scott Bjerg, Ymers ±, showing main geological features. Key in Fig. 8.

3) 1500 m green sandstone, lower part passes into 2
2) 50 m red and green sandstone, passes locally into 1
1) 0–50 m conglomerate, only locally present
unconformity
Cambro-Ordovician limestones

The red and green sandstone contains important intervals of red very fine sandstone.

Scott Bjerg

This is the name given by us a to mountain (Fig. 1) to the south of the western end of Duséns Fjord. Like Heintz Bjerg and Hammeren to the north, Scott Bjerg has a simple structure (Fig. 10). The Devonian strata dip at about 30° to the south-southeast. We found a number of small, normal faults associated with the unconformity.

On the col to the west of the summit of Scott Bjerg, the Devonian conglomerate is in contact with Pre-Devonian rocks along a sharp, near-vertical surface.

The succession (3000 m) on Scott Bjerg is as follows:

top of the succession
6) 1400 m green sandstone
5) 200 m red sandstone
4) 1000 m green sandstone
3) 250 m green and red sandstone
2) 100 m conglomerate and red sandstone
1) more than 50 m conglomerate
unconformity

Our total thickness of 3000 m compares with an estimate of 3500–4000 m by Bütler (1948, p. 117).

The conglomerate (1) appears to thicken northwards. Unit (1) passes laterally into unit (2), and unit (3) passes laterally into unit (4).

The total Devonian thickness below the Kap Graah Group on the south side of Duséns Fjord is about 3000 m, yet, on the north side of the fjord which is about 5 km wide, the equivalent strata are only 1600 m thick. This indicates the presence of a major fault striking along the fjord, and downthrowing probably to the south. A group of faults has been described in Noa Dal (Eha, 1953, p. 38), which is the westward continuation of Duséns Fjord.

Angelins Bjerg

There is a sharp discontinuity in the rocks on the western face of Angelins Bjerg, when it is viewed from the west. Darker green rocks above appear to be faulted against paler green ones below. This fault seems to be the northward continuation of the major fault on Eastern Rødebjerg, but does not appear to continue further north to the southern side of Duséns Fjord.

On the western ridge of Angelins Bjerg, a sharp monocline is exposed at an altitude of about 1000 m. Strata dip at about 60° to the southwest, over a horizontal distance of at least 350 m.

We have compiled the following general succession (980 m)for the western part of Angelins Bjerg, from two separate altimeter sections:

top of the succession
5) 60 m upper red sandstone
4) 150 m white sandstone
3) 200–250 m middle red sandstone
2) 400–500 m grey green sandstone
1) 20 m lower red sandstone
base of exposures

The sediments of eastern Angelins Bjerg are green, except for a few red bands at an altitude of about 1500 m. This eastern succession is about 1500 m thick, but may include significant faulting. The red sediments of the west then, must pass into this generally green succession to the east. Indeed the lower and upper red sandstones (1 and 5) listed above appear to pass into green beds from one side to the other of the monoclinal fold described above on western Angelins Bjerg.

Rødebjerg

In the westernmost valley of Rødebjerg, there is a well formed monocline dipping steeply westwards, in contrast to the generally flat strata of this ridge. This monocline may be the same as the one described on western Angelins Bjerg.

The main structure of Rødebjerg is farther east and is an anticline with its axial surface striking at 330°, and dipping at 70° to the east. The axial plunge is 20° to the north. A number of small anticlines occur on the limbs of this main structure. The commonest strike direction for their axial surfaces is northeast, but other directions include north-

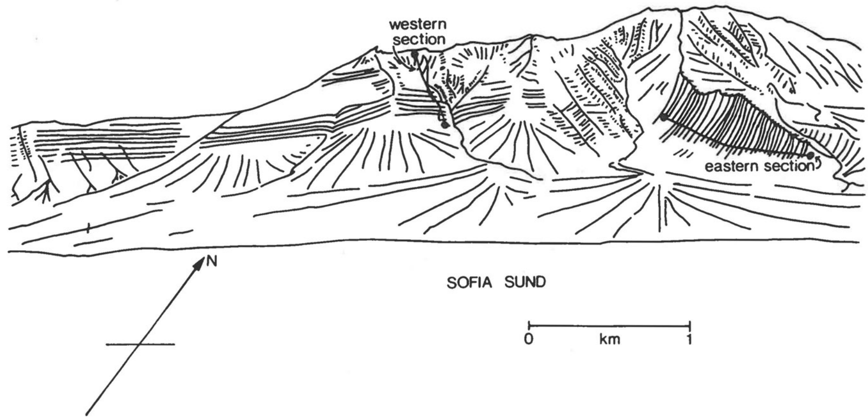

Fig. 11. Sketch of Rødebjerg, Ymers Ø, from south-west. Heavier lines indicate bedding. The positions of the two sections, listed in the text, are shown.

northwest and east-northeast. The strata on the eastern flank of the main anticline dip at 50° to the east (direction 105°), and this dip decreases to 15° further to the east. The strata on the western side of the main anticline are vertical from the core of the fold to a point west of the highest peak of the mountain. Further west the strata are more or less horizontal (Fig. 11).

In the vertical strata to the west of the anticlinal axis, a complex series of five near-parallel strike-slip faults was mapped. The dominant sense of movement was sinistral (from local folds and from the displacement of the mappable horizons within vertical strata) and the modal direction of strike on the fault surfaces is northwest (325°). The total amount of lateral displacement is of the order of 250 m.

Bütler (1935, p. 27, fig. 13) described a thrust fault to the east of the main anticlinal axis. At the location he indicated, there is a valley trending north-northwest. The rocks of the east side of this valley are green sandstones that appear more massive than the folded rocks of the western side. Exposures in the floor of the valley at a height of 640 m. are brecciated and show a number of small folds that indicate some strike-slip sinistral movement. But this is the only direct evidence we have of movement in this area.

Two small, parallel faults were found about 500 m to the east of the valley just described. Red siltstone units are displaced at these faults and this indicates a dip-slip, reverse, component of movement.

On the west ridge of Rødebjerg, the following section (1770 m) was measured (Fig. 11):

top of exposures
670 m upper red sandstone*
100 m variegated (red and white) sandstone

200 m white sandstone
200 m lower red sandstone
500 m green and brown sandstone
100 m green sandstone
base of exposures

To the east of the position of BÜTLER's "thrust", we measured an entirely different sequence (2500 m) (Fig. 11):

top of exposures
500 m yellow-green sandstone
50 m yellow sandstone
150 m red sandstone*
500–1000 m upper green sandstone
200–300 m green and red sandstone
500 m lower green sandstone
base of exposures, near the position of BÜTLER's "Thrust".

It is not possible to suggest a correlation between these successions using local evidence. But from the north a discontinuity can be seen cutting obliquely across the face of the mountain, and we suggest that this is the outcrop of the northward continuation of BÜTLERS "thrust". Below the discontinuity, the strata appear continuous and more or less flat. This demonstrates that the main Rødebjerg anticline, so prominent a structure on the south side of the mountain, does not exist on its north side. But from the point of view of understanding the correlation and the sedimentary relationships another observation is more important. When viewed from the north the western ridge of the mountain displays a lateral transition between red strata in the west, and green strata in the east.

The same facies change can be seen on the south side of the mountain when the red sandstone of the eastern succession is examined in detail. At the point where the eastern ridge of Rødebjerg appears to be highest, the 150 m red sandstone (* above) consists of two red bands separated by a green band. This green band passes into red strata westwards, and the lower red band passes into green strata to the east. We suggest that the 150 m red sandstone on the ridge passes westwards into the thick (670 m) upper red sandstone of the western succession (* above).

Svedenborgs Bjerg

The exposures on Svedenborgs Bjerg are excellent, but the tectonic structures are very complex.

The geology of north Svedenborgs Bjerg, the south wall of Sofia Sund, is summarised in Fig. 12. A succession for this area may be synthesised as follows:

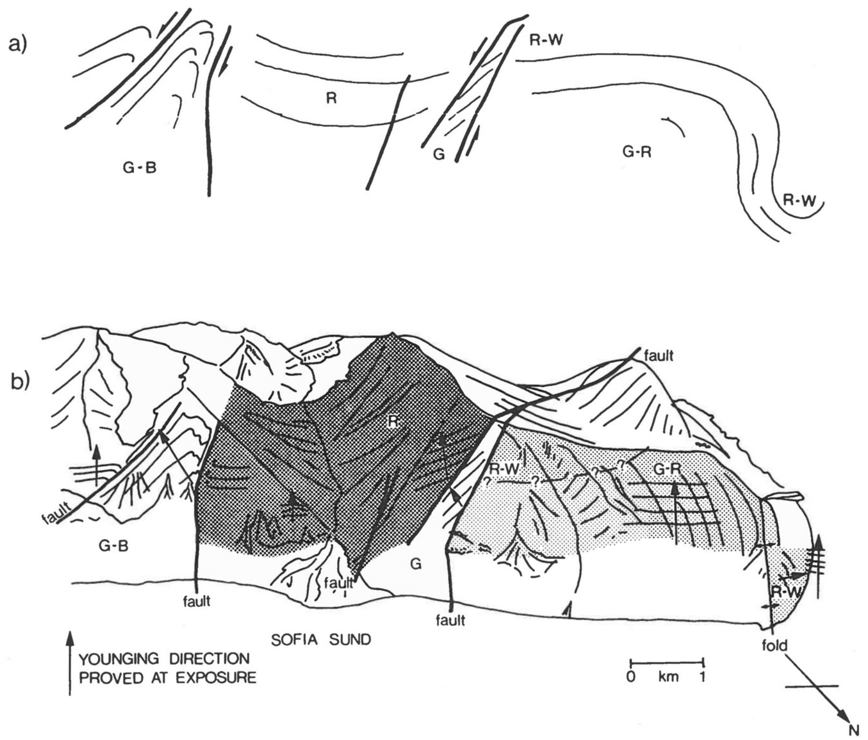

Fig. 12. Northern face of Svedenborgs Bjerg, north-western Geographical Society Ø. G, green sandstone; G–B, green and brown sandstone; G–R, green and red sandstone; R, red sandstone; R–W, red and white sandstone. a) diagram of probable structure; b) sketch from aerial photographs.

top of succession
5) 600 m red sandstone
4) 500 m green and brown sandstone (passes laterally into 5)
fault
3) 100 m green sandstone
fault
2) 200 m red and white sandstone
1) 500 m green and red sandstone
base of exposures

The west face of Svedenborgs Bjerg is illustrated in Fig. 13. At the southwest corner of the mountain, there are outcrops of about 300 m of red siltstone and very fine sandstone. This unit is overlain by 600 m of green sandstone, which contains a short distance to the north, three 10 to 20 m thick bands of pink sandstone.

Some kilometres north of this, just south of the mouth of the central valley of western Svedenborgs Bjerg, red and white sandstones form the vertical western limb of an anticline, that is the southward continuation

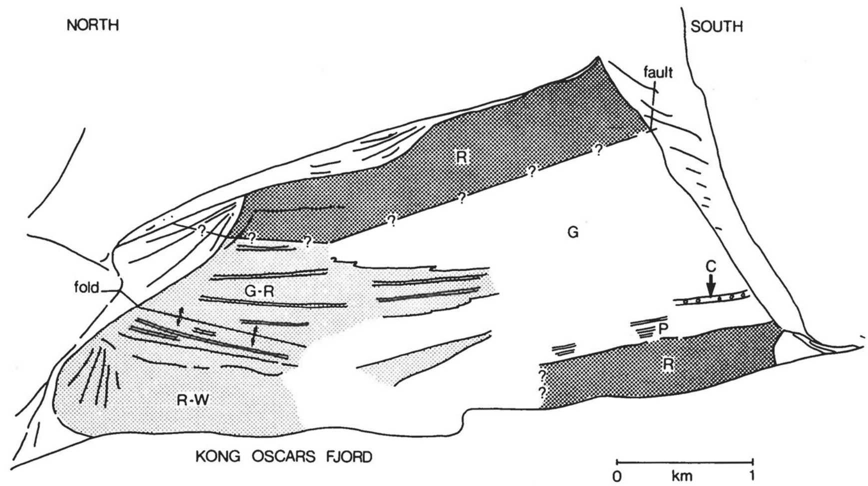

Fig. 13. Southern part of western face of Svedenborgs Bjerg, western Geographical Society Ø. The central valley emerges on the left side of this sketch. C, conglomerate; G, green sandstone; G–R, green and red sandstone; P, pink sandstone; R, red sandstone; R–W, red and white sandstone.

of the anticline described on the western end of the north face of Svedenborgs Bjerg. The core of the anticline is formed of green and red sandstone, and these beds can be seen passing southwards into green sandstones on the face of western Svedenborgs Bjerg, as shown in Fig. 13.

In the central valley on the west of Svedenborgs Bjerg, the structure and succession are summarised as follows:

top of outcrops
7) more than 400 m, upper red sandstone
fault
6) 50 m upper green sandstone
fault
5) more than 120 m lower red sandstone
4) 100 m grey sandstone
3) 100 m red and white sandstone
2) 200 m lower green sandstone
1) more than 300 m, green and red sandstone
base of outcrops

We suggest a correlation for these three Svendenborgs Bjerg sections in our later synthesis (Fig. 18). This synthesis depends on evidence of lateral passage, and on the making of assumptions about the displacement effects of faults. This evidence is presented more fully by YEATS in his unpublished PhD thesis (1971, University of Cambridge), and will not be presented here. One structural conclusion of importance is that the simplest stratigraphic reconstructions often require fault movements with reverse dip-slip and strike-slip components.

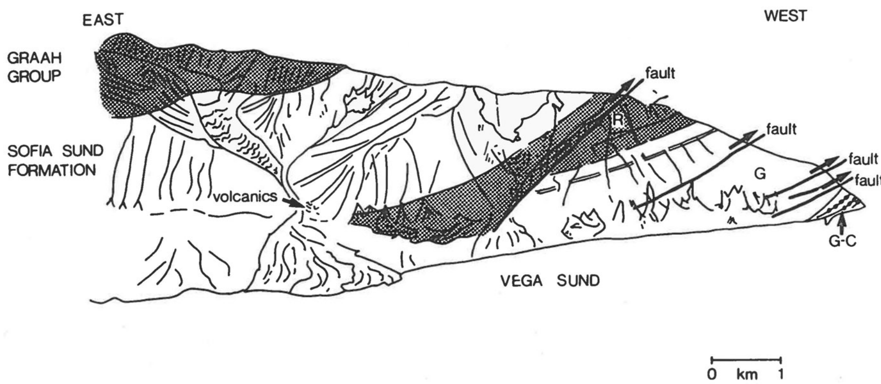

Fig. 14. Sketch of north face of Rebild, north-western Traill Ø. G, green sandstones; G–C, green sandstone and conglomerate; R, red sandstone.

Kongeborgen

Kongeborgen is the name (Fig. 1) of the wall of Devonian rocks that dominates Kong Oscars Fjord, on northern Traill Ø.

The northern end of Kongeborgen adjoins the mountain range of Rebild that lies to the south of Vega Sund.

The structure and stratigraphy of western Rebild is clearly important in that it provides a section normal to the northern end of the Kongeborgen range. It is summarised in Fig. 14. A major fault runs down to a valley mouth some 5 km east of the northwest corner of Traill Ø. The fault surface dips at a low angle to the southeast, and its outcrop can be traced continuously to the summit ridge, where BÜTLER (1959, p. 69) noted it at an altitude of 1450 m. Beneath the fault surface, exposures in the valley just mentioned include a number of small folds, with axes trending southwest and south-southeast. BÜTLER (1935, p. 30) suggested that there were two stress directions acting on the Kongeborgen area, one north-south, and the other east-west.

Similar faults to this major one occur lower on the north-western ridge of Rebild (Fig. 14). There are also three small asymmetrical anticlines, indicating movement towards the north or north-northwest. These folds have been cut by a strike-slip fault.

BÜTLER (1955, p. 69 and Tafel 10) reports an overturned anticline low in the entrance of the valley that emerges near the northwest corner of Traill Ø. However, way-up criteria in the strata show that no overturned strata are present.

The succession on northwest Rebild is summarised as follows:

top of outcrops
5) 500 m red sandstone (Kap Graah Group)
4) 1000 m white sandstone
3) 500 m red sandstone

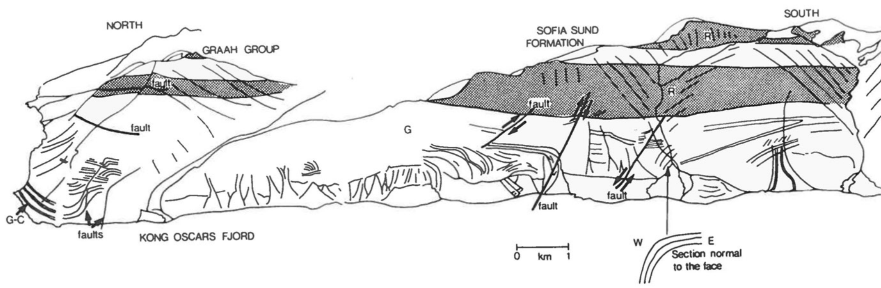

Fig. 15. Sketch of western face of north Kongeborgen, north-western Traill Ø. G, green sandstone; G–C, green sandstone and conglomerare; R, red sandstone.

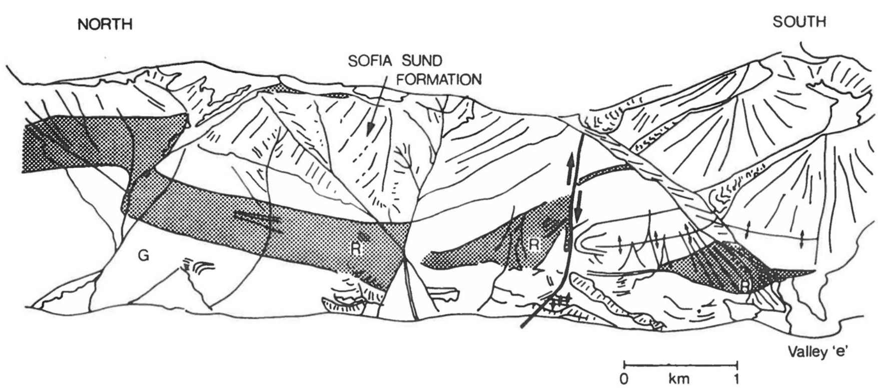

Fig. 16. Sketch of west face of central Kongeborgen, north-western Traill Ø. G, green sandstone; R, red sandstone.

2) ? hundred m green sandstone
1) ? hundred m green sandstone and conglomerate
base of outcrops

The thicknesses of units 1 and 2 cannot be specified because of the presence of low-angle faults. An amygdaloidal lava, about 5 m thick, and with a scoriaceous top, occurs at the base of the white sandstone unit (4) in the floor of a major valley 7 km east of the northwest corner of Traill Ø. The conglomerates in unit (1) are thin (1 m, 4 m and 30 m thick) and well spaced through the sandstone unit.

Fig. 15 is a sketch of the stratigraphy and structural features of Kongeborgen southwards from the north-west corner of Traill Ø just described. Fig. 16 continues this sketch down as far as the valley known as "Valley e" by Bütler (1955). This was the next locality at which we spent time studying outcrops in detail.

We shall therefore report some detailed observations from the area of "Valley e". At the entrance to the valley, is a large westward facing anticline with its axial surface striking at 185° and dipping at about 30°

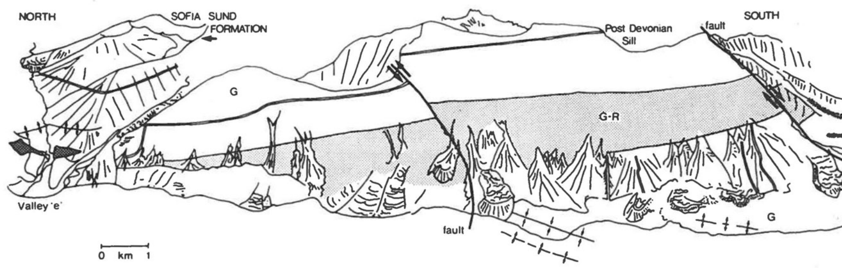

Fig. 17. Sketch of west face of southern Kongeborgen, north-western Traill Ø. G, green sandstone; G–R, green and red sandstone.

to the east. The westward limb of this anticline is overturned and dips at 50° to the northeast, whereas the eastward limb dips at 30° to the north-northeast. This eastward, upper limb, is cut by several faults striking generally southeast, and these may have had a strike-slip component of movement.

To the west of the main cliff of Kongeborgen, and north of the mouth of "valley e", there are several small folds. All have vertical axial surfaces that strike northeast or east-northeast. This area of folding and the one previously described suggest two distinct stress directions, from the west-southwest and from the south-southeast.

The succession (1970 m +) in the area of "valley e" is summarised as follows:

top of outcrops
7) 1000 m { cream sandstone
6) { upper red sandstone
5) 120 m upper white sandstone
4) 50–100 m yellow green sandstone
3) 200 m lower white sandstone, with thin conglomerate beds
2) 50 m lower red sandstone, thins to 5 m northwards
1) more than 500 m, green sandstone
base of outcrops

The most obvious structures in southern Kongeborgen (Fig. 17) are two major fault zones. The first of these is about 3 km south of "Valley e" and it consists of a single normal fault striking north-northwest and downthrowing to the west. The second zone defines the southern limit of the Devonian outcrops of Kongeborgen. This zone consists of a least two near-parallel faults striking due north, and downthrowing Carboniferous rocks to the east. Both fault zones are demonstrably late in age because they cut post-Devonian intrusions or strata.

There is no folding in the main cliff of southern Kongeborgen, and the bedding dips generally at about 25° to the northeast. By the shore to the west of the main cliff (Fig. 17) are a number of small folds, generally with parallel axes, and sometimes overturned to the west. The modal trend of the axes of these folds is northeast. Bütler (1955 Tafel X) illustrated a large westward facing anticline at the base of the Kongeborgen cliff, but we found no evidence for this, and think that the geometry of the jointing in the strata may have given this impression.

The succession (1400 m +) in southern Kongeborgen is summarised as follows:

top of outcrops
more that 300 m upper green sandstone
300–700 m, green and red sandstone
more than 400 m lower green sandstone
base of outcrops

Summarising the structural features of Kongeborgen, the higher strata in the south, are relatively undeformed, except where they have been cut by major, post Devonian fault zones. In contrast the lower, and more northerly strata show a variety of structures, some of them indicating considerable crustal strain. These suggest compressive stresses from the southeast in the south, and overturning and compression from the east and south-southeast further north. Northwesterly trending later strike-slip faults are also a feature of this more strongly deformed area.

Isolated conglomeratic outliers

There are four isolated areas of conglomerate outcrop. They are described in more detail in the next section of this paper.

Munotbjerg. 150 m of conglomerate lies on an irregular Eleonore Bay Group (pre-Cambrian) limestone topography. In the north of the area there is 30 m of red sandstone.

Ella Ø. The conglomerate on Ella Ø is 1000 m thick and lies on Cambro-Ordovician limestone topography. Near the unconformity there are several isolated breccia outcrops and interbedded with the conglomerates are four silt and limestone bands about 5 m thick.

Hammars Ø and Åkerbloms Ø. The conglomerate outcrops on these two islands are only about 20 m thick. On the west of Åkerbloms Ø there are 15 m of breccia lying on the limestone topography.

Syltoppene. Approximately 20 m of conglomerate lies on a very irregular topography. This is overlain by perhaps 300 m of red sandstone, which contains several thin bands of conglomerate.

General correlation

The problems of local lithostratigraphical correlation have been demonstrated in the descriptions just given, and any overall correlation must obviously be a tentative one.

We have made the assumption that the various outliers of red

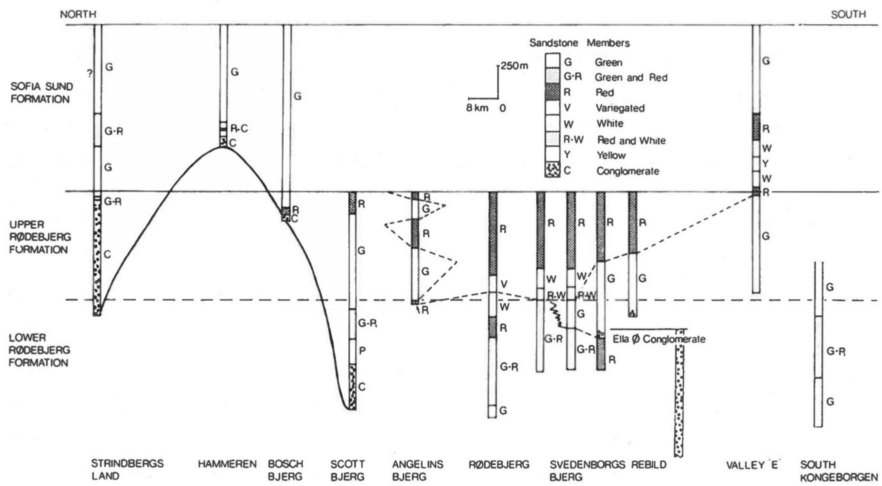

Fig. 18. Attempt at correlation of the successions of Kap Kolthoff Supergroup i the western sequence.

sandstones attributed by Bütler (1965) and Koch and Haller (1971) to the Kap Graah Group do in fact belong to that Group. We have then used this as a datum, and concentrated our efforts on correlating the strata beneath this datum. Fig. 18 presents the results of this correlation. As sub-divisions of the Kap Kolthoff Supergroup we have defined the Sofia Sund and the Upper and Lower Rødebjerg Formations, and the lithologic and stratigraphic grounds for these definitions are clear in Fig. 18 (See also Table 11).

This chart (Fig. 18) shows that the top of the highest red unit forms an important marker from Scott Bjerg in the north to "Valley e" in the south. This marker corresponds to an important change of grain size and often, also, to a change of palaeocurrent trend.

The thick succession in Strindbergs Land presents a problem in correlation because it lacks any outcrops of Kap Graah type. It sposition on the chart (Fig. 18) is highly speculative.

The correlation of the isolated conglomerate outliers presents another problem. On Ella Ø transport of material was towards the east, and in this direction thin conglomerates are found in the sandstone successions of southern Svedenborgs Bjerg and Rebild (north end of Kongeborgen). The limestone clast composition of the lower part of the thick Ella Ø conglomerate suggests that it correlates with the lower part of the Svedenborg Bjerg green sandstone (Fig. 18). The only link possible with the Munotbjerg conglomerate outlier is by way of a thin conglomerate exposed to the east in the gorge of Fladedal. This may be equivalent to the lower red sandstone on Angelins Bjerg. There is no evidence to allow the correlation of the other conglomerate outliers with the main sandstone sequences.

Some general points about the deformation of the western margin

The major change in sediment thickness between the Hammeren succession and that of Scott Bjerg and other more southerly successions is made clear in Fig. 18. We call this feature of the western margin the Hammeren horst. The great thickness of the Strindbergs Land succession indicates that the horst has a northern edge in the area of Keiser Franz Josephs Fjord.

Although the horst was active during Middle and Upper Devonian sedimentation, it was also an important factor influencing later deformation. From Hammeren to Scott Bjerg, the marginal Devonian is slightly tilted but otherwise largely undeformed. In contrast, south of this area, the lower parts of the successions are characterised by complex faulting, folding and overfolding along a zone east of Kong Oscars Fjord.

The details of these structures have not been adequately investigated to provide a coherent regional picture, but they appear to provide evidence (Fig. 19) for deformation of the margin of the Devonian basin in at least two different senses:

1) reverse dip-slip—resulting in overturning and overthrusting of Devonian strata westwards towards the basement exposures of the basin edge.

2) more minor left-lateral strike-slip—resulting in movement of the basin-fill northwards relative to the basement.

These effects are sporadically and locally apparent in structures that show a lack of continuity and overall pattern. This lack may be characteristic of the deformation of thick, but variable, clastic sequences close to the surface.

Why was it that the sediments on the Hammeren horst largely avoided the deformation? This may reflect the higher proportion of rather finer grained, probably relatively incompetent, rocks in the successions south of the horst and the relative strength of the thinner horst successions.

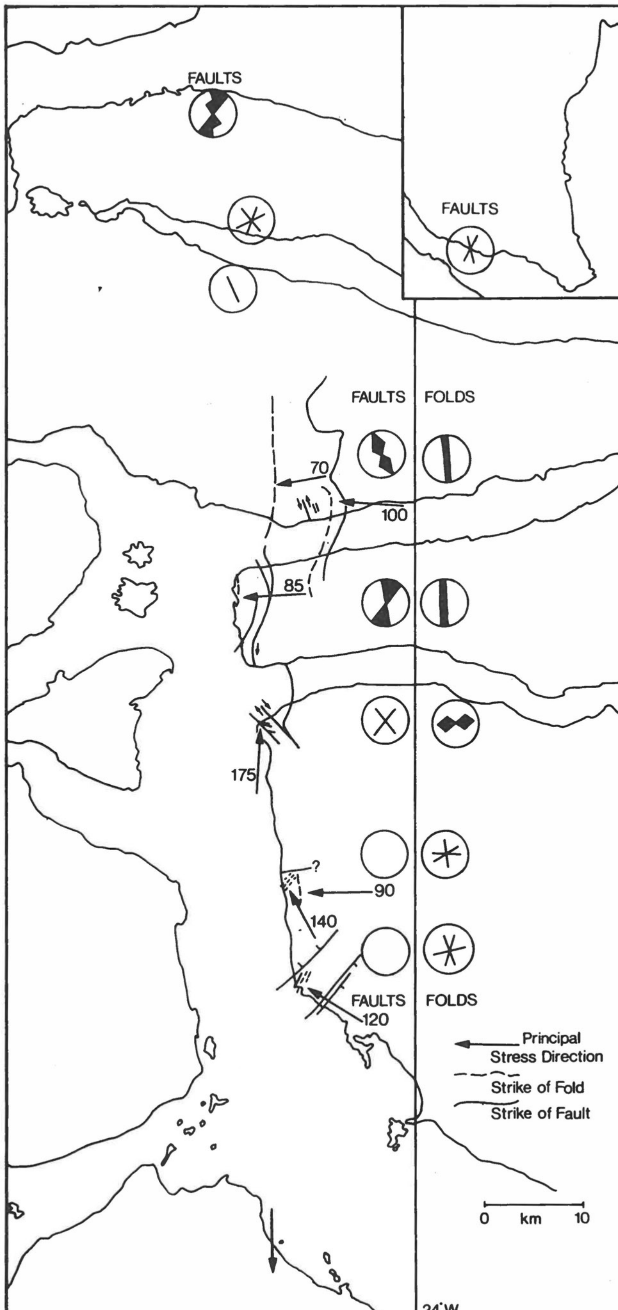

Fig. 19. Summary of some structural data from the western sequence outcrops. Azimuths of measurements are summarised in the circles for the different areas.

CONGLOMERATES AND THE UNCONFORMITY

Introduction

The distribution of conglomerate outcrops along the western margin is shown in Fig. 1. The best exposure is on Ella Ø, and this will be described first in some detail. The remaining conglomerate localities will then be examined starting from the north and moving south, and a final section will discuss conglomerates that occur in dominantly sandstone successions.

We have measured conglomerate clast size, angularity and composition using a procedure which consisted of selecting sample areas from exposures roughly perpendicular to bedding. These areas were generally 50 cm by 50 cm $(50\ cm)^2$, but sometimes 10 m by 10 m $(10\ m)^2$ where very large clasts were present. Where we have quoted "mean maximum" clast measurements, these are the means of the measurements for the ten largest clasts in the sample area. In some cases we have quoted clast size using the product (eg. 3500 cm^2) of the apparent long dimension and the longest dimension perpendicular to it. In these cases we have often also quoted the square root of this product (eg. 59 cm by 59 cm) to help the reader visualise the general size of the clasts.

Conglomerates and associated lithologies on Ella Ø

In the southeast of Ella Ø, Devonian conglomerates with minor breccias, limestones and siltstones lie unconformably on Cambro-Ordovician limestones. The Devonian outcrop area is about 40 square kilometres (Fig. 20), and the succession is about 1000 m thick. The breccias, limestones and siltstones are only found within the lowest 200 m of the succession.

Conglomerates

Almost all the conglomerates are of framework type i.e. the clasts were deposited more or less in contact with their neighbours. This can be checked high in the Ella Ø succession where the matrix of the conglomerates is commonly friable enough to allow dissection of the rock by hand. In these outcrops quartzite clasts often show solution pits at their points of mutual contact. A general estimate of the proportion of clasts to matrix is about 4 to 1, by volume.

The matrix of these conglomerates is generally red and finegrained (typically very fine sand grade). The smallest clasts are about 1 cm in diameter, so that the conglomerate as a whole (clasts and matrix) is notably bimodal in grain size distribution.

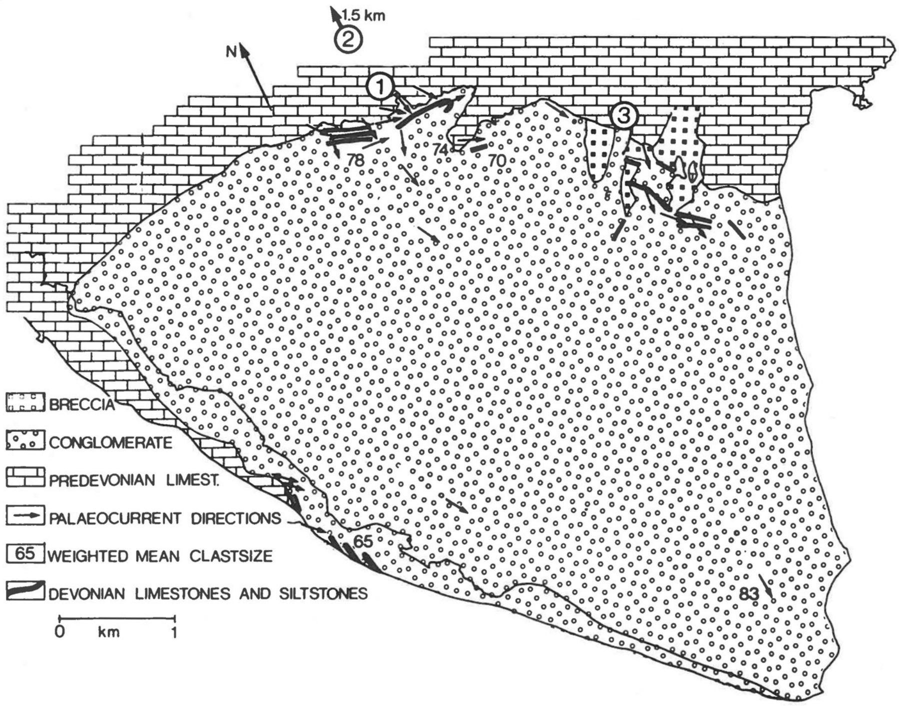

Fig. 20. Geological sketch-map of south-eastern Ella Ø. Numbers in circles refer to localities described in detail. Other numbers are measures of clast size discussed in text.

Most clasts have a fairly high sphericity (0.6), and imbrication of the clasts is not normally apparent.

Sandstone lenses are the most abundant structures seen in these conglomerates. They range up to 0.5 m in thickness, between 1 m and 10 m in width, and up to 50 m in length. Their bases usually appear to be scour surfaces cut into the underlying conglomerate. Most frequently their grain size is the same as that of the matrix of the surrounding conglomerate. Usually the sandstone lenses have no internal structure, but large-scale cross-stratification and small current ripples occur locally.

In rare cases, we noted more complex occurrences of sandstone lenses. In some cases lenticular conglomerate and sandstone bodies are interlayered and locally there is evidence of lateral deposition of sandstone against interbedded conglomerates and sandstones.

Parting surfaces are another feature of some of the conglomerates. The contact surfaces between conglomerates and sandstone lenses or siltstone and limestone sequences are an important class of parting surface, and parting surfaces separating two units of conglomerate are a particularly notable feature of many finergrained conglomerates.

Cross-bedding in sediments of conglomerate grade is rare, and generally restricted to conglomerates with smaller pebbles. A unit of this sort often occurs above a unit of structureless coarser conglomerate.

BLUCK (1967, p. 142) plotted conglomerate bed thickness against maximum clast size, and found a linear relationship ($r = 0.73$) which he took to show that the "amount of material transported and deposited—increases with increase in competence". We have plotted observations of clast size against parting surface interval. Because r, the correlation coefficient, is only 0.5, we conclude that our observations, at least when lumped together, do not provide convincing support for BLUCK's discovery.

Within our Greenland conglomerate outcrops, we can distinguish a *coarse conglomerate* type. This is characterised by clasts up to 1 m across, but normally 10 to 20 cm, numerous sandstone lenses, rather rare parting surfaces, and very rare cross-bedding. All the structural evidence points to aqueous deposition: we have no evidence for debris flow ("mudflow") deposition. Modern environments which we regard as analogous are those of braided stream gravel accumulation (WILLIAMS & RUST, 1969; KRIGSTROM, 1962; FAHNESTOCK, 1963), and we ourselves have briefly examined comperable braided stream deposition in Iceland. The coarse bed-load in these environments is transported during periods of peak flow (FAHNESTOCK, 1963, p. 27), and bars form most rapidly at high stage. We have waded at low stage in Icelandic and Greenland braided streams, which had deposited coarse gravel. We have not seen, or felt, large cobbles or boulders in motion, but there is much transport of silt and sand. Small anabranches erode the bars (KRIGSTROM, 1962) and are infilled with sand on being abandoned. Minor channels, comparable with "dead sloughs" (HICKIN, 1969) exhibit linguoid ripple formation and shooting flow from which plane beds are deposited. These minor channels, which modify previously formed high stage bars, are probably the origin of our sandstone lenses.

We can also distinguish a *fine conglomerate* type. This is characterised by clasts up to 5 cm across, few sandstone lenses, large numbers of parting surfaces, and fairly common cross-stratification. We have found no description of a satisfactory modern analogue for this deposition. The smaller clast size suggests lower flow velocity or power, and the cross-bedding indicates the presence and systematic down-stream building of sand-gravel bars. The frequent parting surfaces imply the prevalence of fluvial reworking, i.e. erosion and redeposition of the alluvium, on a rather greater scale than in the coarse conglomerate environment.

We investigated vertical variation in the conglomerate by logging the highest 400 m in the succession in southeastern Ella Ø. Fig. 21

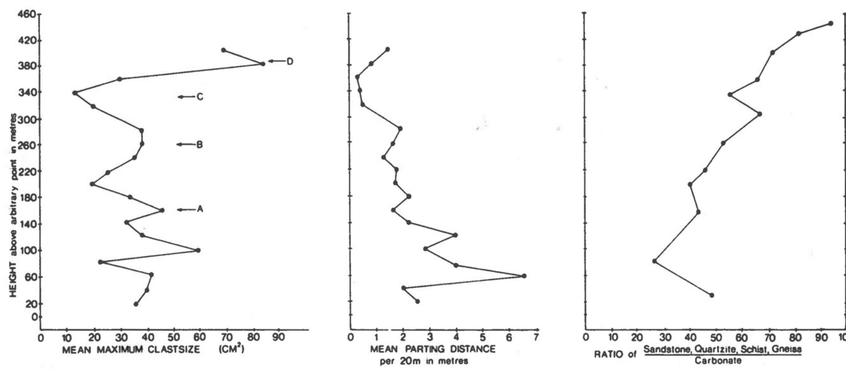

Fig. 21. Variation in certain features of a long section in the conglomerates of southeastern Ella Ø. A, B, C, D refer to important events in accumulation sequence.

shows the mean maximum grain size recorded every 20 m. We examined grain size variation further by dividing up the vertical sequence of grain size means into intervals of equal thickness, and then using an F test (Bartlett, 1937; Griffiths, 1967) to determine whether the succeeding interval's values belonged to the same population. At 1 $^0/_0$ confidence level, intervals from 136 to 185 m, 220 to 270 m, 320 to 350 m, 350 m upwards, were those of most significant change. Further analysis allows us to locate important events at 160 m, 260 m, 330 m and 385 m, and these are labelled A, B, C and D in Fig. 21. We also examined variation in parting surface separation in the same succession (Fig. 21). This showed an upward decrease in separation, significant at the 1 $^0/_0$ level, if the sequence is divided into four and tested using "F".

Five clast types were recognised in the field:

a) *Yellow dolostone* – mainly from the Cambro-Ordovician

b) *Black limestone* – mainly from the Limestone-Dolomite Series of the Eleonore Bay Group

c) *Red sandstone and shale* – mainly from the Lower Cambrian, the Tillite Group, and the Multicoloured Series of the Eleonore Bay Group

d) *Schists* (feldspar-biotite-chlorite) and *vein-quartz* – probably from Lower Eleonore Bay Group metamorphic sources

e) *Pebbly mudstone* – from the Tillite Group. Only one clast of this type was found by us.

The most obvious variation in clast composition occurs at the very top of the succession on Ella Ø where the clast size and parting distance increase. About 10 m after this increase, schist and vein quartz clasts are encountered for the first time and there are no black limestone clasts.

This composition change coupled with the increase in grain size suggests uplift of the source area. The palaeocurrent indicators show that the sediment was derived from the northwest. The uplift may have been a component of tectonic movements that formed the normal faults, downthrowing to the east, which bound the metamorphic zone of Pre-Cambrian rocks.

An examination of the geological map (KOCH & HALLER, 1971) shows that, to the northwest of the Ella Ø conglomerate, the nearest source material is the Cambro-Ordovician limestones and the most distant the metamorphic crystallines and the Multicoloured Series. The Limestone-Dolomite Series of the Eleonore Bay Group is intermediate. The ratio of red sandstones, vein quartz and crystallines to dolostone and limestone may be a function of the amount of material being derived from different parts of the possible source area. Fig. 21 illustrates the variation of this ratio, each point being an average of four analyses. The curve is surprisingly smooth and shows a gradual increase in the percentage of the more distant red sandstone, vein quartz and crystalline rocks. The more distant part of the source area became more important with time. This implies that the river was eroding its head waters. There are temporary increases in the schist and red sandstone component associated with peaks A and B (Fig. 21).

A single horizon of conglomerate was traced for about 2 km and clast size measurements were made. Vertical sections were measured through this unit. It was found that the vertical variation was great and no systematic lateral change could be detected.

A weighted mean maximum clast size was found for 5 sections at different locations and at different levels in the Ella Ø conglomerate outlier (Fig. 20) and this shows a slight suggestion that grain size decreases distally. However, because the sections are at different stratigraphic levels, any trend must be influenced by vertical variation, and it has not been possible to assess the importance of this.

Breccias

The location of breccias along the unconformity is shown in Fig. 20, and more detailed sketch maps show more precisely the relationships between outcrops.

In the northwest of Fig. 22, near K005, there is a small gorge 40 m deep and 45 m wide, cut into Ordovician Limestone, and it can be traced to the north for about 85 m.

Further north, small red veinlets are found on the limestone surface and these veinlets occur sporadically along a zone that extends for about 2 km, where, between two small lakes, an outcrop of breccia is encountered (locality 2, fig. 20). The breccia forms a ribbon 20 m–40 m wide and 10 m–

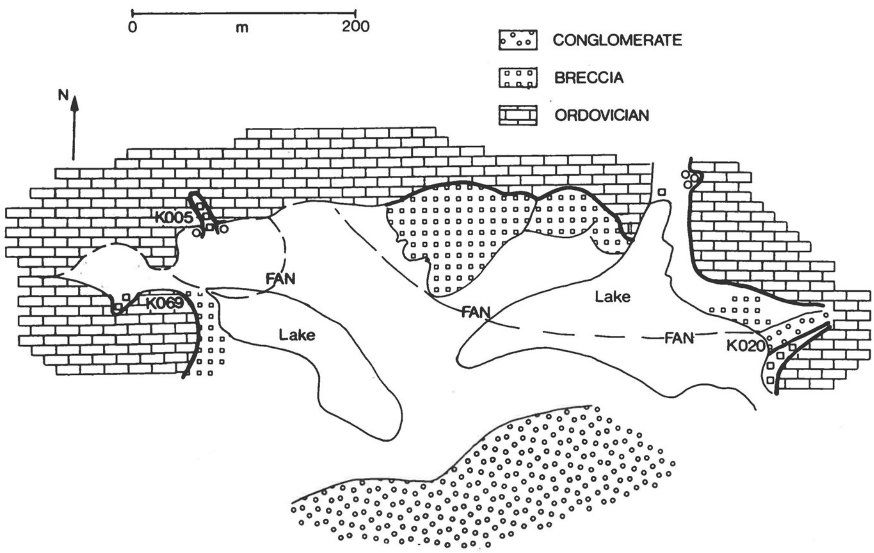

Fig. 22. Sketch map of conglomerate/breccia outcrops of area (1), Ella Ø, indicated on Fig. 20.

15 m deep. The breccia clasts range in size from 5 cm to 4 m in diameter and are angular to sub-angular. The clast lithologies are of red limestone, yellow dolostone, and limestone with siliceous nodule layers. The varied composition indicates that some of the clasts were transported from another area. The local limestone near the breccia shows red veining and some fragments appear to have been fractured almost in their present position. These breccia deposits formed in a Devonian gully or ravine within the limestone bed-rock topography.

The relationship between the lithologies seen in the gorge at K005, to the south, is more complicated. Conglomerates and breccias are interbedded and the breccias are in large lenses, implying scouring of conglomerate by a current before the deposition of a breccia or another conglomerate. The mean maximum grain size of the conglomerates for a 50 cm square sample ranged from 40 cm^2 to 75 cm^2 whereas some of the breccia clasts were as large as 40 cm in diameter. There are clasts of quartzite as well as limestone in the conglomerate; quartzite was not found in the breccias. Abundant sand lenses were encountered in the conglomerate but no palaeocurrent indicators were found. It seems likely that the breccia was transported from the north and the conglomerate was an extension of the main conglomerate, which outcrops approximately 200 m further south.

The breccia outcrops further east (Fig. 22) are all poorly exposed. Single clasts range in diameter from 10 cm–20 cm to 3 m, and are all of limestone. No sedimentary structures were found. It is not possible to

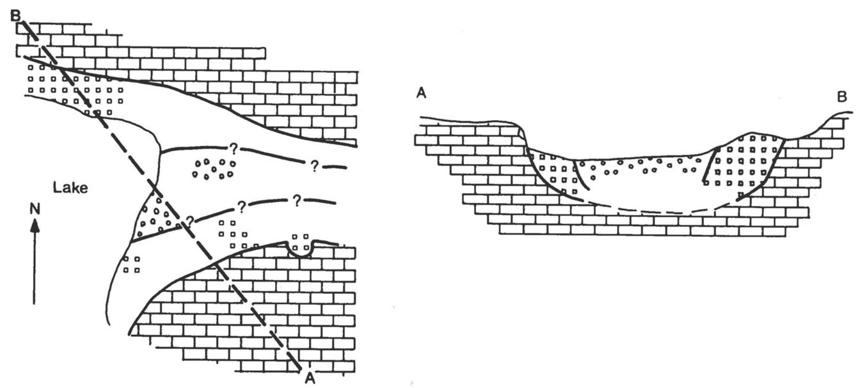

Fig. 23. Sketch map and section of breccia, conglomerate and Cambrian and Ordovician limestones, locality K020 on Fig. 22.

be certain of the exact form of these deposits but, by analogy with breccias examined on Heintz Bjerg, there were probably two fans, which are sketched on to Fig. 22.

To the east of these two fans, there is an area of conglomerate which is flanked on either side by (Fig. 23) breccia.

The breccia infills joints in the limestones and rests on little ledges. The conglomerate and breccia infill a valley and it is thought that the conglomerate was an extension of the main conglomerate mass.

2 km further east there is another area of breccia outcrops (locality 3 of fig. 20). These have the form of knolls, each up to 50 m high, separated by marshes with no exposure. It seems clear that these knolls are fragments of a single irregular body of breccia. This body was eroded by the river system which formed the conglomerate because the conglomerate fills a small valley within the breccia.

The surface of the breccia is highly weathered but two types can be recognised on the basis of composition. We distinguished 'monomict breccia' which consists entirely of grey limestone, and 'polymict breccia' which has clasts of several types of limestone.

The clast size in the polymict breccia ranges from 1 cm to 60 cm diameter whereas clasts as large as 5 m are found in the monomict breccia. Both breccias show a 'trachytic' texture in the small clasts; that is, the small clasts are sometimes subparallel. Sandstone lenses are only found in the polymict breccia and they are small and deformed. The properties of the two breccia types are summarized opposite:

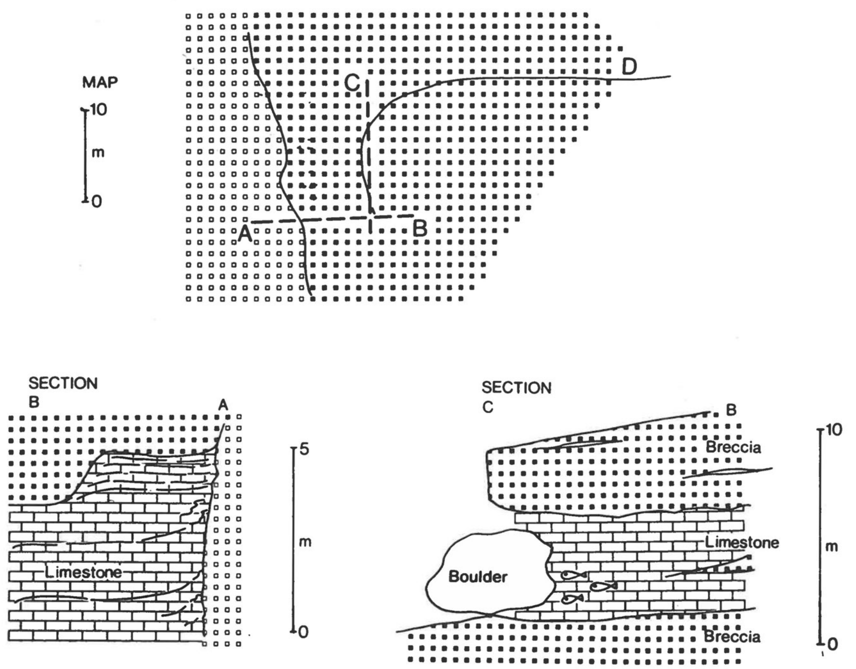

Fig. 24. Sketch map and two sections showing relationships between Devonian limestone, conglomerates and breccia, north of locality 3, Ella Ø, indicated in Fig. 20.

	Monomict	Polymict
Clast size	1 cm–5 m	1 cm–60 cm
Composition	All one type lst.	Several types lst.
Roundness	Angular	Angular
Modality (of grain size)	Bimodal	Bimodal
Matrix	Very fine sand	Very fine sand
Fabric	Trachytic	Trachytic
Framework of clasts	Yes	Yes
Gradations within bed	None	Indistinct vertical decrease in grain size
Sand lens	None	Rare

Conglomerates and intervals of silt and limestone are found in the neighbourhood of these breccias. The silts and limestones (described in detail below) form bands up to 5 m thick and these are seen in contact with the breccia in several localities. Fig. 24 illustrates one of these contacts. The fine deposits are both older and younger than polymict breccia and abut the monomict breccia. There are elongate lobate scours at the base of the higher polymict breccia. Similar relationships are seen at another locality. Some breccia, then, was being deposited at a

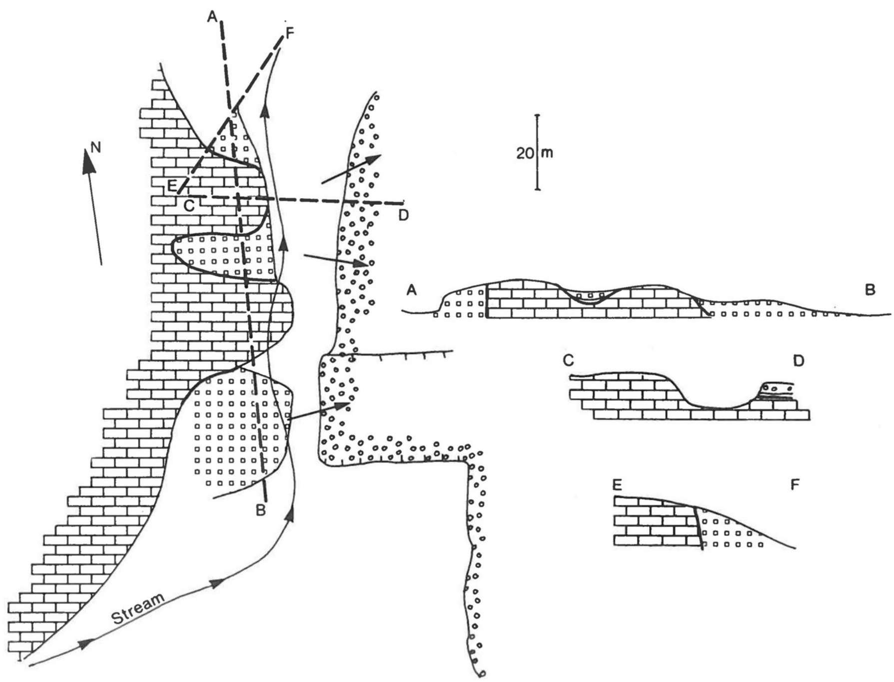

Fig. 25. Sketch map and two sections showing relationships between conglomerates and breccias and "basement" (Cambrian-Ordovician limestones). Locality in K069, Ella Ø (Fig. 22).

similar time to the formation of the finer horizons. Because several fine grained beds are interbedded with conglomerate, the conglomerates and breccias are probably more or less contemporaneous. This is confirmed, where breccias, conglomerates and fine deposits are all interbedded.

Further northwest a few angular clasts are incorporated in the conglomerate near the breccia.

The only palaeocurrent indicators found in this area suggest a northeasterly source for the breccia and a northwesterly one for the conglomerate.

As with all breccia deposits, it is difficult to deduce the mode of deposition of these rocks. The presence of a trachytic texture in the finer clasts typifies deposition by a river or by a mud or debris flow. Hooke (1967) describes debris flows and considers that they can be recognized in the field by their poor sorting and lack of stratification and the presence of cobbles and boulders in a matrix of fine material. It is possible that our monomict breccia is a debris flow deposit.

Sand lenses, a scoured base, and the small maximum grain size of the polymict breccia are similar to features found in the conglomerates which are thought to be deposits of rivers. Hooke (1967) states that in

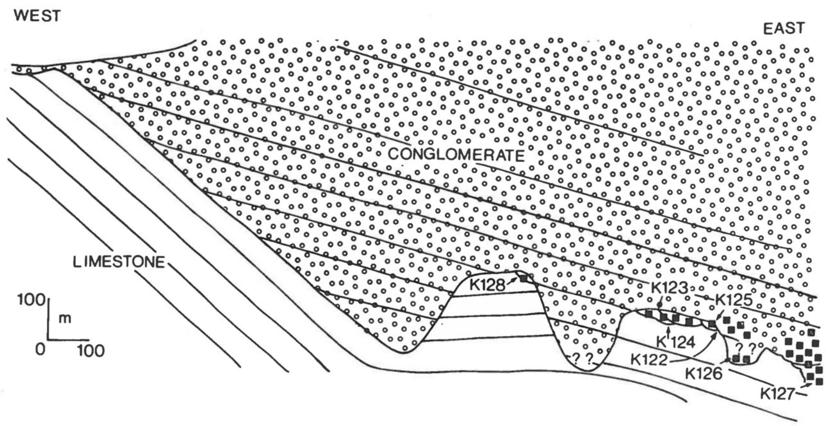

Fig. 26. Sketch of part of south-cliff of Ella Ø, forming the north wall of Narhvalsund. Conglomerates and breccias rest on a very irregular topography of "basement" (Cambrian-Ordovician limestones). K numbers mark localities.

the Pliocene Ridge Basin Group (CROWELL, 1955), debris flow deposits pass distally into fluvially bedded conglomerates. The contrast in composition between the monomict and the polymict breccias indicates a more distant source for the latter.

100 m south of the gorge at K005 in Fig. 22 is another group of breccia outcrops at K069 (Fig. 25). The body of breccia is wedge shaped and about 5 m thick. In it the clast size decreases from 50 cm at the base to 1–5 cm at the top, but the finer horizons do contain some coarser clasts. There is a crude bedding which is picked out by layers of clasts of similar size and these dip at about 15°. The clasts are all of the same type of limestone; they have a very low sphericity though the corners are rounded. The matrix is of medium sand. This breccia may have been deposited from debris flow.

Further south there is a tongue shaped outcrop with an appearance of bedding approximately 60 cm thick. The beds are curved concave upwards across the outcrop. These beds may be formed by a debris flow or by fluvial action and are similar to the bedded breccias found on Åkerbloms Ø (see below). Some of the clasts at the contact between the limestone and the breccia have a similar orientation to the country rocks. The clasts are separated from the country rock by a fine breccia with a red calcite cement, and the small limestone clasts in the matrix show no trachytic texture. These clasts may have been preserved in the process of breaking away from the country rock.

At an altitude of approximately 450 m, approximately 1 km west, there is another small outcrop of breccia. This breccia was deposited in the lowest part of a small valley.

The only other outcrops of breccia found on Ella Ø are on the enormous cliff exposures north of Narhvalsund, and these are shown in Fig. 26. At K127, there are three units of rudaceous rocks. At the base, there is 40 cm of breccia with mainly black limestone clasts, the largest of which is 40 cm in diameter. The mean maximum grain size is 2–5 cm, and there are a few dolostone and red sandstone clasts. The matrix is calcareous and there are a few beds of finer clast size which are, in some cases, cross-bedded and have a generally lenticular form. Overlying this breccia is an erosion surface with a relief of approximately 10 m. This forms a base for a second breccia containing 2 m diameter, black limestone clasts which have a low sphericity and poor sorting. There are some dolostone clasts. The matrix is again strongly calcareous. The third unit is a normal coarse conglomerate, which forms the majority of the cliff.

The lowest breccia was probably deposited by fluvial processes and the second unit may have been formed by either a debris or a fluvial flow.

At K122, the unconformity is broken up by red veins, and clasts of black limestone are seen almost in situ. Immediately above this there is a black limestone breccia. This black limestone breccia is seen again at K125, where it cross-cuts a dolostone breccia. The matrix of this latter breccia varies from coarse silt to fine sand in grade. The underlying dolostone breccia is about 13 m thick and has a framework with clasts up to 2 m in diameter. The fine sand matrix contains small angular chips of dolostone. The depositional mode of these two deposits is uncertain.

There is a small outcrop of dolostone breccia at K126.

In the main conglomerate, there is a slight dip to the east, and it therefore seems likely that the black limestone breccia at K125, K122 and the second division of K127 may be the same horizon. This would suggest that these were the deposits of smaller local streams within valleys which were later submerged by the black limestone breccia. The dolostone conglomerate at K124 may be fluvial or a debris flow deposit.

The general interpretation of these breccia deposits and their relationships to the conglomerates are elucidated by consideration of a locality visited by us in Iceland. The locality is Thorsmark, to the southwest of Myrdalsjökull in South Iceland. An east-west trending valley contains a coarse gravel braided river (Krossa), of which the channel complex has a high sinuosity and meanders across the valley. Entering the valley from the south are several smaller streams, Strakagil, Hvanna, and Strakkholtsgja, which deposit small, 300 m radius, fans. The gradient of these fans is steeper than that of the main river Krossa, and the clasts are coarser (up to 1 m) though still rounded. The Krossa runs westwards into a larger valley, the Markarfljot, which is crossed by a sandy-pebbly braided river extending southwards onto a sandur plain many tens of kilometres wide. Some of the Ella Ø breccias were probably formed in small side fans like the Hvanna, the main conglomerates accumulating in a river system in some ways comparable with the Krossa. Conglomerate-sandstone contacts to be discussed below, e.g. at Rebild (Kongeborgen), probably formed in situations like those where the Krossa joints the Markarfljot. Others of the Ella Ø breccias may have been formed by the flow of debris off the steep slopes locally cut in the outcropping Ordovician limestones.

Limestone and siltstone

This is the least abundant lithological association on Ella Ø and the distribution is shown in Figs. 20 and 29. It is found in bands up to 7 m thick and ls always overlain by a coarse conglomerate. In some localities only limestone is found and in others only silt and sandstones, but they can be interbedded.

Rare beds of conglomerate, from 1 cm to 35 cm thick, are inter-bedded with all the fine-grained lithologies. The clasts are always fine-grained, 1 cm to 5 cm, and no sandstone lenses or other internal structures are observed.

Sandstone beds are normally very thin (approximately 10 cm), but locally may form 1–4 m units in some of the thicker fine-grained units.

Very fine-grained sand is the most abundant sand grade. Asymmetrical ripples and plane beds are the predominant internal structures, as in the mainly sandy units in our area. The central portions of some ripples appear to have moved diapirically and been eroded by the subsequent bed. The sandstone is predominantly red.

Loading structures, such as squamiform load casts (Pettijohn & Potter, 1964 plate 59B) and torose load casts (ibid, plate 54B), are fairly abundant. Frondescent scours (ibid, plate 68), groove casts (ibid, plate 61, prod casts (ibid, plate 66), and flute casts are common in some sections.

Red and green siltstones are very common and are mainly plane bedded. Some beds contain abundant small white and red oval concretions from .25 to 2 mm in diameter, which form in crude horizontal layers. In thin section, the angular quartz grains sometimes float in a matrix of calcite, 50 $^0/_0$ of the rock being quartz; however they sometimes form a framework. Chlorite, muscovite, limestone and quartzite grains also occur.

The concretions are stained red by a fine dissemination of hematite and include quartz grains (cf Friend & Moody-Stuart, 1970, p. 185, fig. 4a). There is no evidence that the siltstone has been pushed aside by growth of the concretions. Single horizons of concretions up to 10 cm thick and several metres in length occur within silt, and the occasional

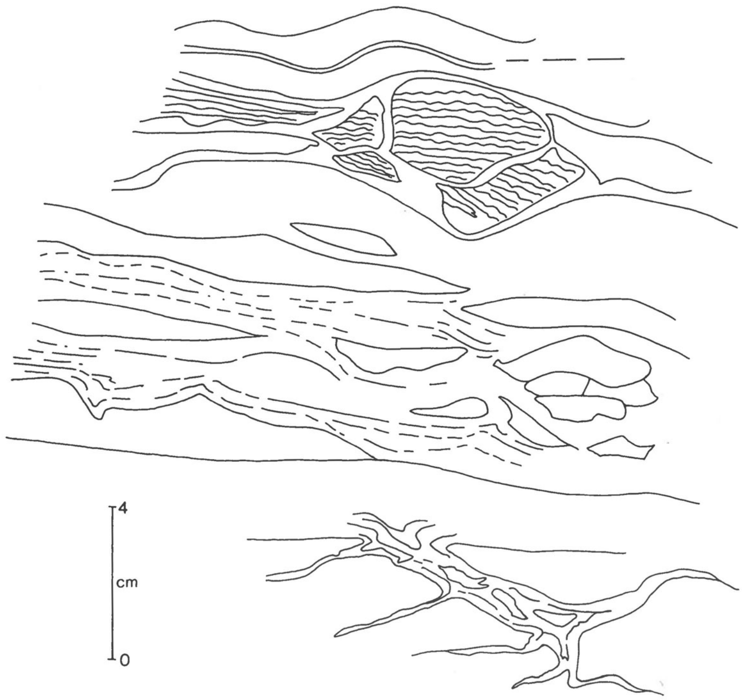

Fig. 27. Sketches of textural features of Devonian limestones, Ella Ø.

thin flat laminated limestone band is found within flat laminated siltstone.

The limestones examined in thin section are very pure, less than 2 % silt being present. No chemical analysis was carried out and the ratio of magnesium to calcium is not known, but rhombs of dolomite have not been observed. Red, green and black limestones were examined in thin section. There are small hematite crystals in the red, and pyrite crystals in the green limestone. The black limestone is very fine-grained and contains some disaggregated plant material. There are three textural types of limestone:

a) About 50 % of the red and black limestones are laminated; the laminae being from 1/2 mm to 3 mm thick. Some laminae are stained by hematite and darker laminae contain stylolite-like surfaces (parallel to laminae) infilled with dark material. Occasionally there are load casts on the base of dark laminae.

b) Black and green limestones containing no internal structures occur but are not common.

c) Some red and black limestones contain abundant ovoid pellets from 1/2 mm to 1 cm in diameter. Most pellets are round but some are angular in form and they appear to be concentrated at particular horixons.

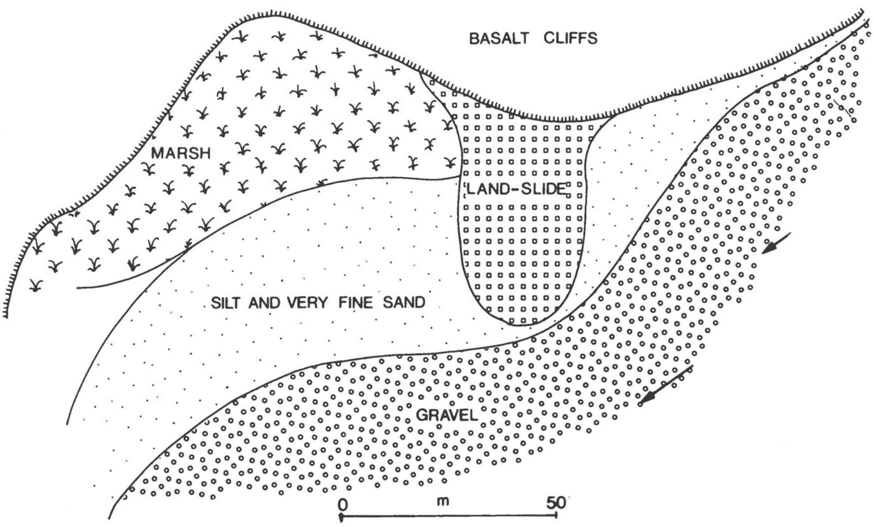

Fig. 28. Sketch maps showing morphology, environments and grain-size in a locality on the western edge of the Skeiderarsandur, central South Iceland. This is based on our own observations.

Long axes of the pellets are apparently sub-parallel. Poor horizontal laminations bend around the pellets or wedge out. Coarse calcite and silt grains are found coating the margins of a few pellets.

These pellets could have been formed as:

(i) faecal pellets. The pellets are all ovoid in thin section but there does not appear to be a concentration of organic material or silt within the pellet, as might be expected if they were feacal.

(ii) burrows. But the pellets are all ovoid in thin section and no burrow forms were seen in the exposure.

(iii) 'in situ' concretions. But the presence of silt halos (FRIEND & MOODY-STUART, 1970) around pellets suggests that they were derived.

(iv) derived concretions. This appears to be the most likely origin (cf FRIEND & MOODY-STUART, 1970). Most beds of limestone, which range in thickness from $^1/_2$ cm to 10 cm, have planar bounding surfaces, but some are irregular and separated by fine silt laminae. In Fig. 27, red limestone with fine parallel laminations is broken up by irregular fractures. The fractures are sometimes infilled with fine silt. They were probably caused by dehydration soon after deposition. The concretions in the silt apparently formed most readily in well-drained sediments, above the mean annual water table (FRIEND & MOODY-STUART, 1970 p. 184). This silt must have been reworked and the concretions deposited in the limestone 'ponds' (cf ibid p. 190) to form pellet limestones. Presumably, the silt was removed in suspension and the larger, heavier concretions deposited.

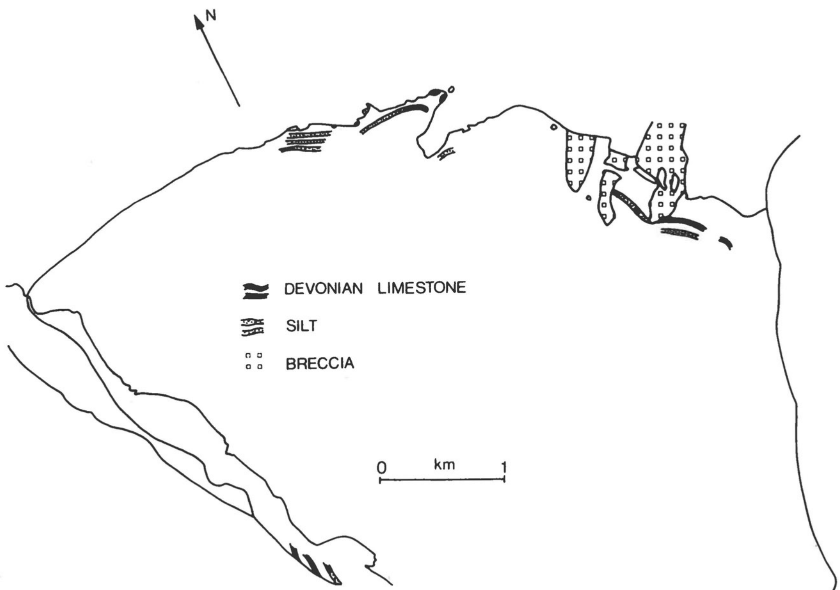

Fig. 29. Sketch map of south-eastern Ella Ø, showing main outcrops of non-conglomeratic Devonian rock types (limestones, silstones and breccias).

It was not possible to determine the geometrical shape of the limestone bodies. They may have been deposited in abandoned channels or as sheets.

It is from these siltstones and limestones, on Ella Ø, that we collected vertebrate fragments (*Glyptolepis* and *Asterolepis*) along with a relatively rich macro-and microflora.

The problem of interpretation of these fine-grained deposits is the relative juxtaposition of these deposits of essentially standing water with the high gradient deposits of the breccias and fluvial conglomerates. We shall now briefly describe a locality in Iceland that provides some insight. The Skeidararsandur is in central South Iceland and is one of the main alluvial spreads extending southwards from the Vatnajökull ice cap. It is a coarse gravel and cobble spread, but, in one locality at its western margin (Fig. 28) it is deflected by a debris flow of coarse boulders that appears to have moved down from the adjacent cliffs of lava. Behind and in front of this debris breccia, silt and very fine sand are being deposited by relatively small streams. It seems that the presence of the breccia body restricts the gradients and maximum flow power available, and allows the deposition of fine-grained sediment. On Ella Ø, the association between the limestone-silt assemblage, the breccia, and the unconformity (Fig. 29) suggests a similar environment, marginal to the main coarse conglomerate alluvial body.

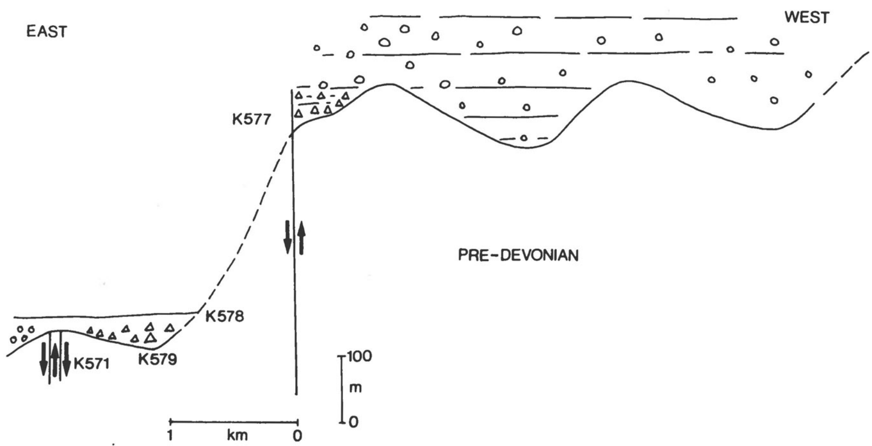

Fig. 30. Diagrammatic section through the unconformity on Hammeren, north Gunnar Anderssons Land.

Hammeren

The north face of Hammeren provides a 5 km long west-east section of the basal unconformity and the overlying breccias and conglomerates (Fig. 30, see also BÜTLER, 1935, fig. 2). Making assumptions about the throw of various faults, we find that the unconformity climbs irregularly westwards along the section, to the extent that almost 500 m of Devonian sediment is overlapped. A number of hollows and valleys characterises the unconformity, averaging $1^{1}/_{2}$ km in width, from crest to crest, and 100 m in depth.

Fine-grained red sandstones of sample group 8 (red- v.f.sst. – flat) and 1A (red – f. sst.-flat) occur with the breccias and conglomerates.

The main body of conglomerate covers the irregularities in the unconformity and was deposited by eastward flowing currents, whereas the flow depositing the main sandstones further east was south-easterly and southerly.

Heintz Bjerg

Breccias, conglomerates and fine-grained sandstones occur above the unconformity exposed to the west of Heintz Bjerg (Fig. 31).

In the main area of breccia outcrop on this map (Fig. 31), there are a number of intervals of red siltstones and sandstones, mainly classifying as 5A (red- v.f.sst.-flat, asym.rip.). These units are 10–15 m thick and locally have been strongly eroded before deposition of overlying breccia.

To the north-west of this main breccia outcrop is a narrow gully cut in the Cambro-Ordovician limestones, and filled with Devonian breccia. This gully is 10–30 m wide, up to 5 m deep, and can be traced for

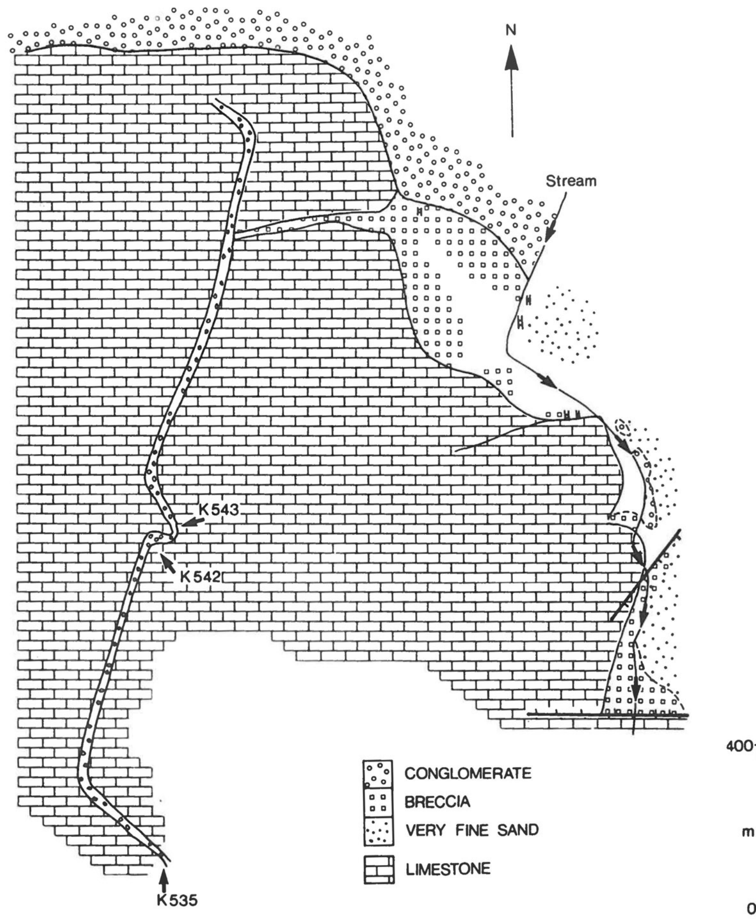

Fig. 31. Sketch map of unconformity to the west of Heintz Bjerg, North Dusèns Fjord. K numbers refer to localitites.

$^1/_2$ km westwards. The breccia fill contains limestone clasts varying from sand-grade up to 8 m across, with an angularity of 0.2 to 0.3.

We conclude that both the main breccia body and the gully-fill were waterlain, because of the partings within the breccia, and the local erosion of the sandstone and siltstone units. The gully may have been a fan-head feature through which the main breccia body was supplied.

Overlying the main breccia and outcropping to the north, is a large area of conglomerate outcrop (Fig. 32). This is a typical bimodal framework conglomerate, with limestone clasts easily distinguished from the matrix of red fine -and medium-grained sand. The mean maximum clast diameter of the clasts is about 15 cm, and their roundness varies from 0.5 to 0.6. In one locality we found a number of metre-thick beds of sand,

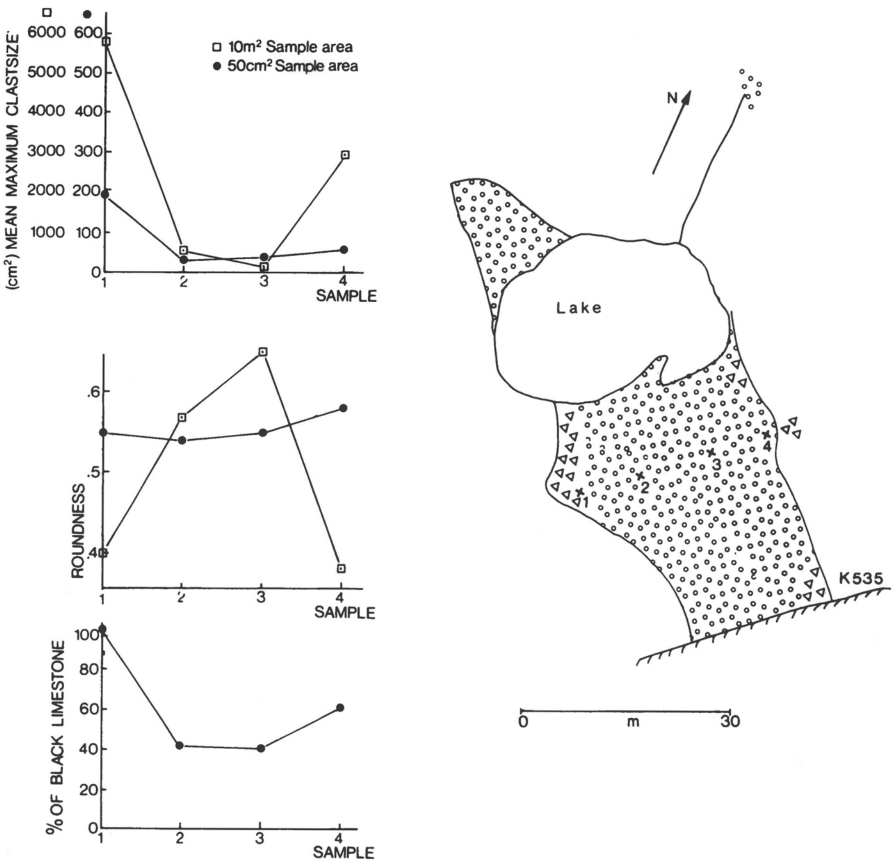

Fig. 32. Sketch map of conglomerate and breccia body on Heintz Bjerg at locality K535, shown on Fig. 43. Three plots show variations in the mean of largest clast sizes, the clast roundness and the °/₀ of black limestone, across the body where indicated. Sample areas are 10 m by 10 m, and 50 cm by 50 cm.

but whether these were deposited by the same river distributaries that depositing areas to the east, is not clear.

Of particular interest is an isolated gully-fill outcrop of conglomerate, shown on the map (Fig. 31) extending northwards from locality K535. The gully fill is about 30 m wide, up to 15 m thick, and extends for almost 2 km. Three sections across the gully were studied, by examining the largest ten clasts in 10 m and 50 cm square sample areas at each of four or five localit ies across each section. The results are presented in Figs. 32 and 33. At locality K535 (Fig. 32), it is clear that the edges of the gully fill are characterised by a higher proportion of black limestone (derived from the local Ordovician basement) than the centre (which contains also light coloured dolomites, quartzites and red limestones). The local derivation and lack of transport of these marginal clasts is also demonstat-

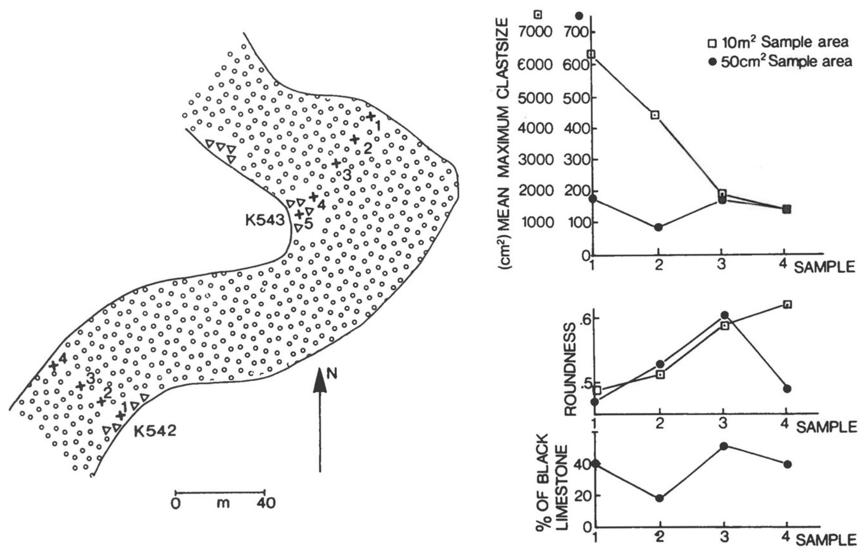

Fig. 33. Sketch map of conglomerate and breccia body on Heintz Bjerg at localities K542 and 543, shown on Fig. 43. Three plots show variation at K542 of the mean of the largest clast size, the clast roundness, and the $^0/_0$ of black limestone. Sample areas as for Fig. 44.

ed by their very large size and high angularity (low roundness). Indeed we think that these large clasts probably fell from the walls of the gully into the main fluvial fill of the gully floor. It is surprising to find that the largest clasts of the central gully fills are better rounded than the smaller clasts. This may have resulted from solution and mechanical attrition of the slowly moving largest clasts.

A similar pattern was found at locality K543 and K542 (Fig. 33) except that, in both cases, the large clasts mainly accumulated on the inside of the bends in the course of the gully.

Scott Bjerg

To the northwest of Scott Bjerg, at the east flank of Rumpen (BÜTLER, 1935 fig. 4), there is a small gorge cut in Cambro-Ordovician limestones, and infilled with Devonian breccia. Low in the succession the breccia has three-modal grain-sizes: a) matrix of very fine sand, b) limestone clasts varying up to 150 cm² (product of diameters of ten largest clasts measured in a 50 cm square sample area) as shown on Fig. 34, c) very large limestone clasts from 60 to 115 cm in mean diameter. Higher in the succession, the clast size decreases, and the very large clasts are absent (Fig. 34). We suggest that this breccia was waterlain, the largest clasts having fallen onto the stream bed from nearby outcrops.

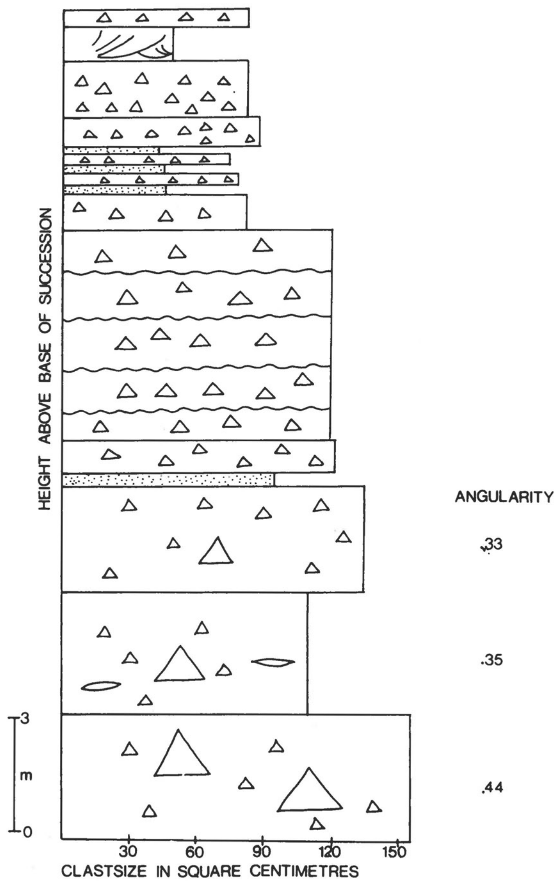

Fig. 34. Section measured through breccia on Scott Bjerg, south of Duséns Fjord.

We studied the main conglomerate body in detail. The clasts are predominantly limestone and dolostone, with small amounts of quartzite and locally of tillite. The mean palaeocurrent vector is directed towards the north-east. Data on clast size were systematically collected, but no clear trends of variation were found. Mean maximum clast size varied from 40 to 123 cm^2 (6 cm to 11 cm mean diameter), with roundness varying from 0.48 to 0.61.

Fig. 35 presents the results of a study of the transition from the conglomerate member up into the overlying red siltstone and very fine red sandstone. The conglomerate clastsize, and the proportion of conglomerate both decrease upwards. In the higher parts of the section, where conglomerate units of 2 or 3 m thickness are separated by fine sandstone units, they extend with no significant thickness variation, over exposures of more than 100 m length in the palaeocurrent direction.

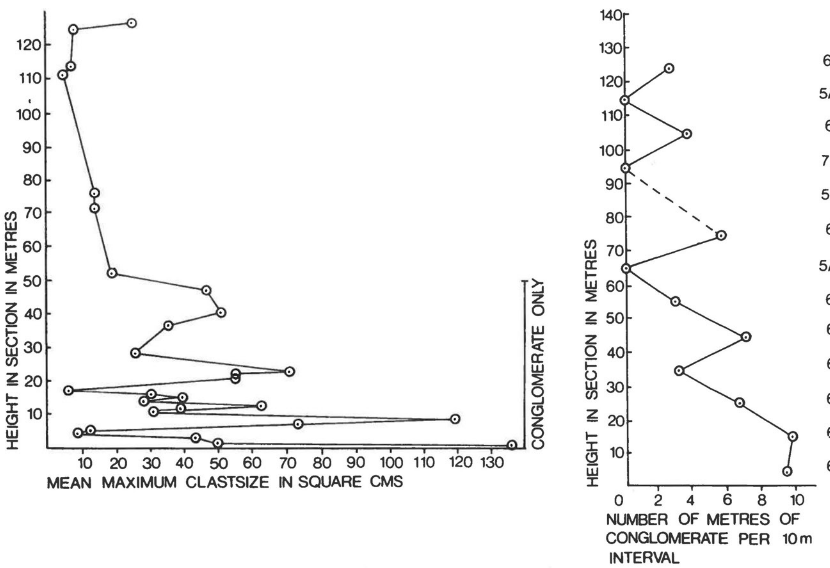

Fig. 35. Section measured on eastern edge of conglomerate outcrop, Scott Bjerg.

Munotbjerg

Conglomerates outcrop between an altitude of 300 m and 900 m on the east side of Munotbjerg. To the northwest outcrops at an altitude of about 1200 m were seen from the air by Eha (1953) and are visible on aerial photographs, but they have not yet been visited.

The conglomerate of the lower outcrops is nowhere more than 200 m thick and the underlying topography formed in the Limestone and Dolomite Series of the Eleonore Bay Group, can be mapped (Fig. 36). Cross-bedding in sandstone lenses in the south of the area, indcates a palaeocurrent direction to the southeast, suggesting that part of the conglomerate at least was deposited by rivers flowing from the north.

Sections through the unconformity are illustrated and located in Figs. 36 and 37. They show a number of valleys with shapes suggested by the contours on Fig. 36. The directions of these valleys appear to have been controlled partly by the strike of the underlying limestone, and partly by a strong joint and fault pattern.

The conglomerates above a small irregularity (section NP on Fig. 37) in the unconformity were studied in detail (Fig. 38). The mean maximum clast size, for 50 cm square sample areas is 14 cm^2 at N, and 86 cm^2 at P, 10 m to the south (4 cm and 9 cm mean diameters respectively), and the number of parting surfaces decreases strongly in the same direction. The presence of an outcrop of pre-Devonian bed-rock clearly influenced the sedimentation and appears to have resulted in the accumulation of a

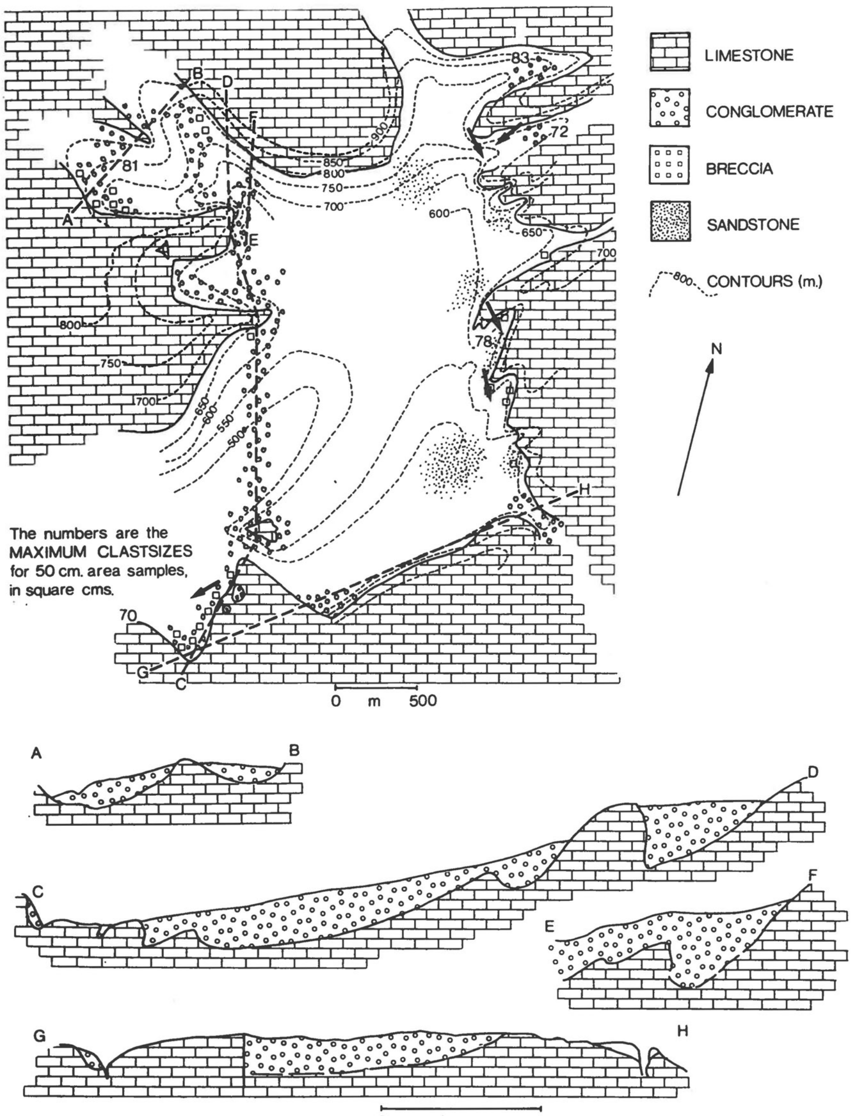

Fig. 36. Sketch map and sections of outlier of Devonian sediments resting unconformably on Eleonore Bay Group limestones, Munotbjerg. Relationship to other localities is shown on Fig. 37. Contours are suggested ones for unconformity.

terrace of thin sheets of finer gravel adjacent to the outcrop. We saw a similar effect at the edge of the Skeidararsandur in Iceland.

On Fig. 36 we have plotted the mean maximum grain sizes for 50 cm square sample areas, but we found no significant trend of variation in this area. Although most of the clasts in the conglomerate are black limestone (50 %) or dolomite (20 %), some quartzite and chert occur. Sand lenses

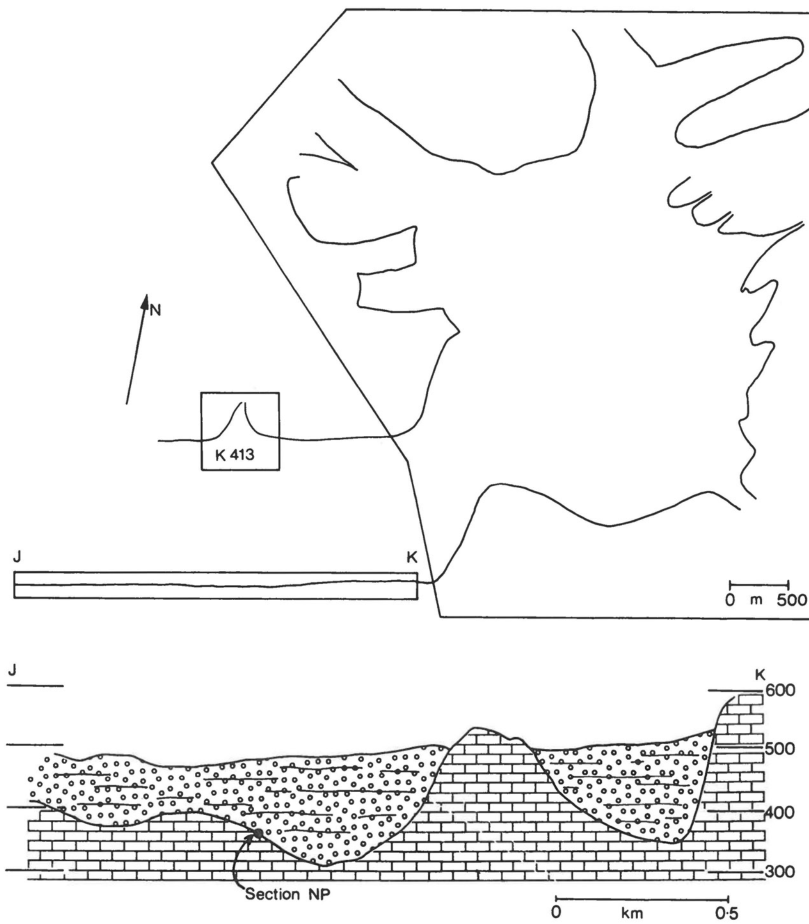

Fig. 37. Index map for Munotbjerg. Devonian outliers. Section along escarpment JK.

are abundant in the conglomerate, and parting surfaces are usually about 1 m apart except close to the unconformity where they are closer to eachother.

Near the unconformity large synclines occur in the conglomerate. For example, near G (Fig. 36), the conglomerate dips at 30° to the north away from the unconformity, while further north it dips to the south. Parting surfaces can be traced from the northerly to the southerly dipping outcrops. Yet the dips in the underlying Eleonore Bay Group limestones do not differ in the two localities. We therefore suggest that the syncline was formed by the compaction of the Devonian conglomerates above the irregular unconformity.

To the southwest (locality K413 of Fig. 37) of the area, there is a gorge eroded into Devonian breccia, conglomerate and Eleonore Bay

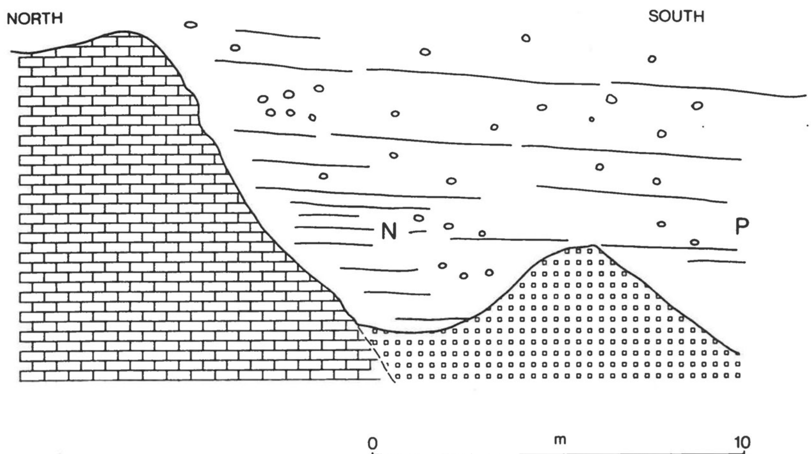

Fig. 38. Section at locality NP of Fig. 37, Munotbjerg.

Group limestones (Fig. 39). The breccia outcrop is approximately 30 m thick and 200 m long and it is overlain by conglomerate from which it is separated by a surface of discontinuity.

The clasts in the breccia are all of local Eleonore Bay Group limestones. The deposit is illustrated in Fig. 39, which shows the variation of mean maximum clast size in 10 m square and 50 cm square sample areas, and of roundness in the smaller sample areas. The largest clasts are at the base of the breccia, the biggest we found being 15 m by 12 m by 10 m. Between the clasts in the breccia there is a matrix of smaller angular limestone pebbles and red very fine sand. In some cases current ripples are visible in this matrix, providing proof of deposition of the matrix from water.

The large clasts in the breccia must have slid into place from the nearby Eleonore Bay Group outcrops. The bedding in these outcrops dips at 33° southwards, and there is a strong joint direction at right angles to this bedding. Large blocks could easily slip down these bedding surfaces. The orientation of the long axes of 20 large clasts was measured and the clasts were found to point modally down or across slope. We saw a similar pattern on a nearby present-day scree.

Red sandstones form the eastern, stratigraphically highest, part of the Devonian outcrop (Fig. 36). They show both cross-stratification, and flat bedding. In some outcrops they contain lenses, from 10 to 50 cm thick, composed of a breccia of small, angular limestone clasts. These are clearly the fills of small hollows or channels, formed by erosion of the underlying sand.

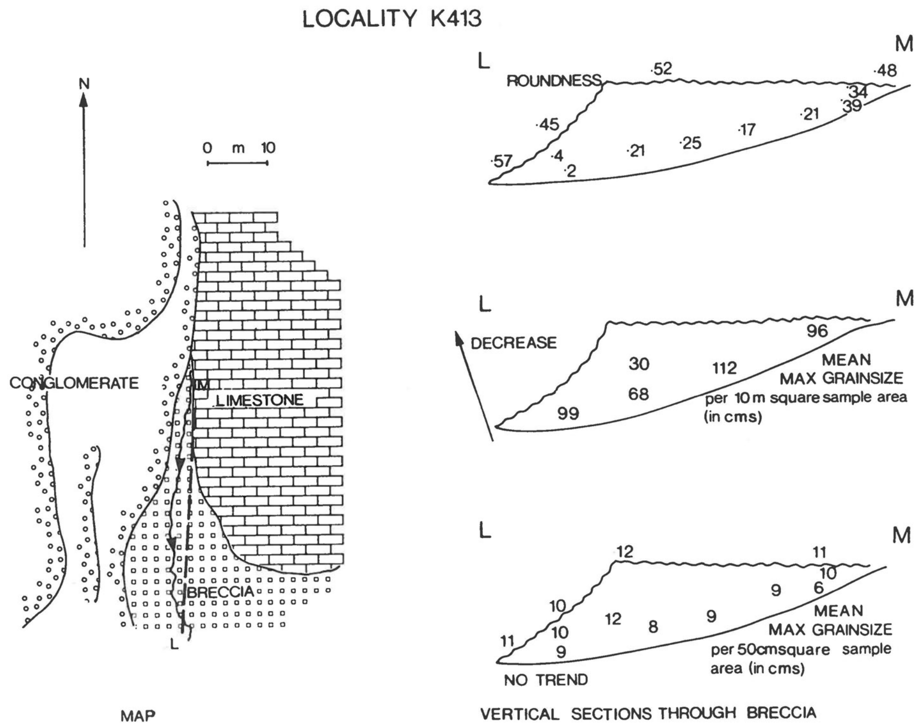

Fig. 39. Sketch map and vertical sections at locality K413 on Fig. 37, Munotbjerg.

Hammars Ø and Åkerbloms Ø

We did not land on Hammers Ø, but sailed close enough to see that it is made of coarse conglomerate.

The eastern part of Åkerbloms Ø is made of Devonian conglomerates with a sandstone sequence below the conglomerates in the northwest. A section through the lower part of the sandstone sequence is shown in Fig. 40. In the upper part of this section there are two units of conglomerate, about 2 m thick. If the succession is followed upwards there are six or seven more of these units before the main body of conglomerates is reached. The interesting question here is the relationship between the rivers that deposited the sandstones and those that deposited the conglomerates. Either they were parts of the same river system, or two different systems. We favour the idea that one system was influenced by local factors such as the presence of pre-Devonian bed-rock topography, so that accumulations of sandstone were locally formed. Structures in the sandstones demonstrate river flows to the north-east.

On western Åkerbloms Ø, Devonian breccias, nowhere more than 20 m thick, outcrop on an irregular topography of the Limestone and Dolomite Series of the Eleonore Bay Group. All the clasts in the breccia

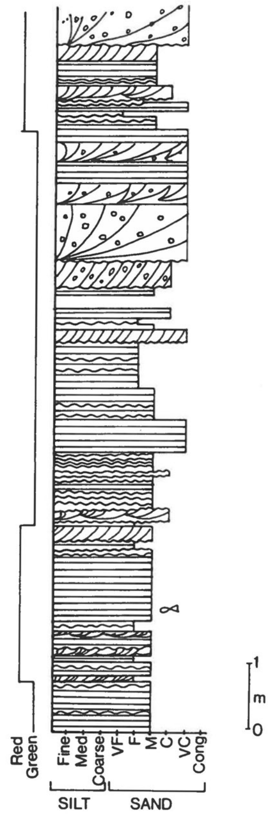

Fig. 40. Sedimentological log measured in lower part of sandstone succession on eastern Åkerbloms Ø.

are of local origin, the largest being 30 to 40 cm in diameter. We suggest that these breccias were laid down by stream flow on a small fan.

Syltoppene

To the north of Syltoppene (Fig. 1), Devonian sandstones have been deposited on a topography formed by the erosion of the Pre-Cambrian Tillite Group and the overlying Cambro-Ordovician quartzites and limestones (Fränkl, 1953 p. 32). Devonian sandstones are found further east and south of the outlier shown in Fig. 41, but we did not visit them.

Sections through the unconformity (Fig. 41) show that there are several small valleys that were progressively infilled by Devonian sediment. The valleys had very steep, sometimes near-vertical sides, and appear to have been eroded preferentially in the softer shale and tillite horizons, so that the ridges between the valleys were formed of limestones and quartzites. The valleys therefore roughly follow the strike of the pre-Devonian rocks.

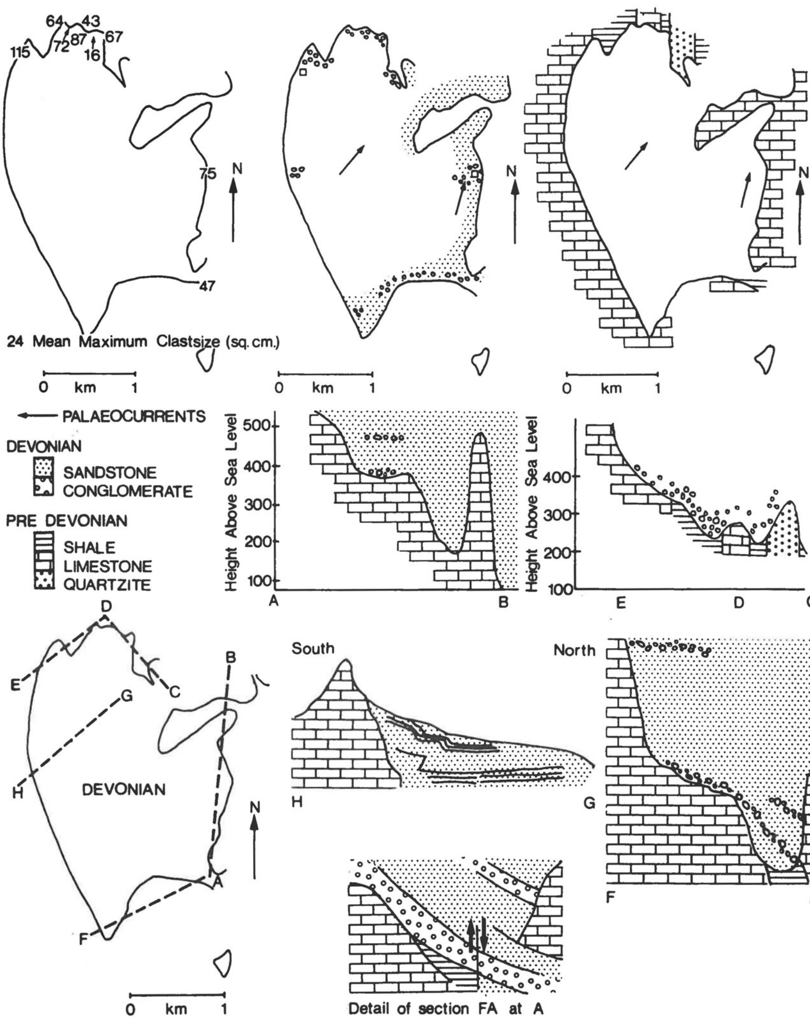

Fig. 41. Sketch maps and sections of Devonian outlier of Syltoppene. a) sketch map showing mean sizes (in cm²) of largest conglomerate clasts, b) sketch map showing palaeocurrents, and distribution of breccias, c) sketch map showing outcrops of pre-Devonian lithologies. The rest of the diagram consists of a number of sections across the outlier, and key map.

In some localities conglomerate overlies the unconformity, in others sandstones are present. The conglomerates show no systematic variation in mean maximum clast size per 50 cm square sample area (Fig. 41a). The clasts of the conglomerate are generally fairly well rounded (0.4 to 0.5). Local influxes of clast material can sometimes be distinguished. At one northern locality large blocks of local quartzite, with a mean maximum clast size per 10 m square sample area of 3500 cm^2 (60 cm by 60 cm)

Table 1. *10 m samples and their properties, Syltoppene*

Section number	red	cgl	max. sand grade	TrX	AsR	Flat	Group	Altitude
K 825	9.8	1.6	medium	1.8	1.4	5.8	8	540 m
	9.3	0	medium	.8	2.8	4.6	5 A	
K824	10	.5	medium	7.2	0	1.6	5A	560 m
K823	10	0	fine	4.3	0	5.2	5A	480 m
K822	9.9	.1	fine	.2	0	9.7	5A	420 m
K821	9.7	.3	fine	.4	0	9.3	5A	
	10	0	fine	.1	0	9.8	5A	
	9.1	4.3	fine	.2	0	5.4	6	370 m

Numbers are total thicknesses in 10 m sample

and a roundness of 0.18, are abundant and were probably deposited by scree fall at the side of a small valley. On the other side of this small valley, there is an outcrop of fine (mean maximum clast size of 16 cm^2 (4 cm by 4 cm) per 50 cm square sample area), angular (.16) breccia, entirely of dolostone.

Other examples were found of angular detritus clearly derived directly from the nearest bed-rock slopes or cliffs. At one locality the very fine-grained sandstone matrix of a breccia showed regular flat lamination undisturbed where it terminates against the angular clasts. This shows that the matrix was deposited by water amongst a framework of already deposited clasts.

Above the unconformity, bands of conglomerate about 1 m to 5 m thick, occur interbedded with the major thicknesses of red sandstones. 10 m sample logs were measured and their properties are summarized in Table 1. They are very similar to the samples of group 5A (red- v.f.sst.-flat, asym. rip) measured on Scott Bjerg, Heintz Bjerg and Svedenborgs Bjerg. On Syltoppene, the sandstone depositing currents flowed to the north-east.

Because this outlier contains sediment that accumulated in the confined space of the floors of a number of interconnecting valleys, it is possible to demonstrate here that river systems capable of transporting and depositing gravel and conglomerate, were also capable, given the right local morphology, of transporting and depositing major thicknesses of fine-grained sand-grade sediment. These conditions of local morphology seem most often to have occurred when sediment first began to build up over the highly irregular topography of pre-Devonian rocks.

Table 2. *Sample group, palaeocurrents and variation of properties, Rebild*

Sample group	Pal	Weighted Mean Grain size	Maximum Grain size	Flat	TrX	Cgl
6		Cgl	Cgl	0		10
6	75	Cgl	Cgl	0		10
6		Medium	Cgl	.9	3	6.2
3D		Medium	Coarse	.3	9.7	0
3D		Medium	Coarse	3.3	6.7	0
3D	32	Medium	Coarse	2.8	7.2	0
3D		Medium	Coarse	3.6	6.4	0

Mean trough cross set thickness 28 cm on 113 sets. 10 % maximum trough cross set thickness 64 cm on 11 sets

Key
Pal – palaeocurrent azimuth
Flat – flat bedding
TrX – trough cross-stratification
Cgl. – conglomerate, Medium and Coarse refer to sandstone grades

Numbers are total thicknesses of 10 m sample

Minor conglomerates in sandstone sequences

Kongeborgen, valley "e"

Two beds of conglomerate occur amongst sandstone of sample group 3D (grey-m.sst.-trough X), both at the entrance to the gorge of valley"e" and at an altitude of 1100 m on the ridge to the north. In the gorge, the se beds are 3.3 m and 0.15 m thick.

Rebild

The succession in the green sandstone and conglomerate member includes at least four units of conglomerate ranging from 1 m to 30 m in thickness. The succession and properties are summarised in Table 2.

The conglomerates have sharp bases which cross-cut stratification in the underlying sandstones of sample group 3D (grey-m.sst.-trough X). Two of the conglomerate units are lens-shaped with a flat top and concave-upwards base, and they extend laterally for distances varying from 16 m to over 100 m. They appear to be the fills of erosional hollows or channel forms.

The large amounts of associated sandstone appear to have been deposited as part of the Kongeborgen fan of the Lower Rødebjerg Formation, and local palaeocurrent measurements demonstrate flow to the northeast. Similar flow directions were measured in the conglomerates, and we see them as the result of a distinct episode of supply of coarse clasts to the fan-head region.

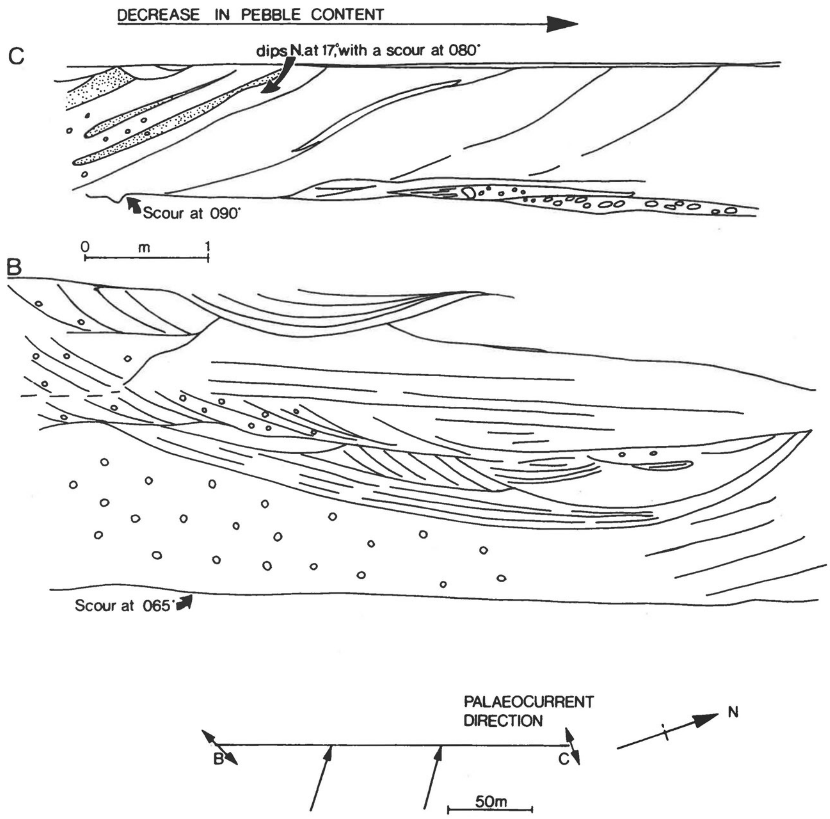

Fig. 42. Sketches and key map for localities with thin conglomerates in Jûluts Dal, west of Rødebjerg.

Svedenborgs Bjerg

We found two conglomerate horizons, about 1 m and 0.5 m thick, in a succession of sample group 3C (grey-m.sst.-trough X), at an altitude of 300 m. They probably formed as tongues of gravel filling hollows in the alluvial surface.

Rødebjerg

Small outcrops of pebbly sandstones and conglomerates can be traced for 200 m in the ravine section on the floor of western Jûluts Dal. Two exposures (B and C) are illustrated in Fig. 42. The conglomerate overlies, with an irregular scoured basal surface, about 15 m of red trough-cross-bedded fine-grained sandstone, which was probably deposited by the wind. The direction of accretion of these aeolian deposits is shown by the two parallel arrows on the location map at the bottom of Fig. 42.

Table 3. *Properties of the sequence of 10 metre samples measured near the base of the Strindbergs Land sandstone succession*

Samples	TrX	Flat	Asr	Cgl	Red	Max. grain size	Max. grain size, cgl omitted	Weighted mean grain size (Ø)
7B	2.1	6.4	.1	.7	3.2	Cgl	Vcss	2.0
7B	.8	7	.3		.1	Medium	Medium	2.9
7B	.3	8.9	.1			Medium	Medium	3.0
2C	8.2	1.6	.1	.6	6.1	Coarse	Coarse	1.8
3D	7.3	2.4	.1			Coarse	Coarse	2.1
8	2	5.9	1.7	.3	10	Cgl	Vcss	1.9
6	4.3	4.9	.3	1.3	9.2	Cgl	Medium	2.6

Properties in metres
Weighted mean grain size: Fine sand, 2–3 Ø
Medium sand, 1–2 Ø
TrX trough cross-bedding
Asr asymmetrical ripples
Cgl Conglomerate; Medium, Coarse, Voss, refer to sandstone grades

Numbers are total thicknesses in 10 m samples

Cross-sets, up to 1.5 m in thickness are a feature of the pebbly outcrop at C. Scour features both at C and at B indicate local flow directions to the east or north-east, whereas the cross-stratification is dipping northwards. We therefore interpret this cross-stratification as the result of lateral deposition on the flanks of a sand and gravel bar. A river system depositing mixed sand and gravel appears to have moved into an area of aeolian dunes, and formed an alluvial morphology of bars and hollows.

Strindbergs Land

The sequence of sample groups and their properties are summarised in Table 3.

One distinctive type of conglomerate in this area consists of massive conglomerate with a fine-grained sand matrix. These conglomerates form distinct units of lens and sheet form.

The second distinctive type of conglomerate is typically cross-stratified and grades into pebbly sandstones. This type occurs with sample group 3D (grey-m. sst.-trough X) and 2C (red, grey-m.sst.-trough X).

We think this latter type may have formed when the dominantly sandy alluvial systems of the main part of the succession impinged on the marginal conglomerate bodies of the first type. Local reworking of the clasts of the conglomerates would explain the occurrence of the cross-stratified conglomeratic and pebbly sandstone type.

Table 4.

	Red	Gn	Fsl	Msl	Csl	Vfss	Fss	Mss	Css	Vcss	Con	Flat	Asr	Plx	Trx	Def	Cnc	Trf	Flst
1A	7.8	4.2			.3	1.5	7.2	2.4	.1			5.2	.9	.9	2.3	.4	.2	.6	.1
1B	8.6	5.7			.1	1.1	7.8	1.1				2.6	.8	1.1	4.8	1.4	.5	.7	
1C	9.7	.5			.1	.4	7.9	1.9	.2			3.1	.1	.1	5.6	1.7			
1D	4.9	8.1		.2	.2	.5	7	2.1	.8			5	.2	1.7	2.7	.7	.1	1.4	
2A	5.2	7.5			.3	1.4	4.5	5.8	.4			3.3	.4	.4	5.2	.7	.3	.2	.2
2B	7.6	6.3		.1	.2	.4	3.8	6.5	1.2	.1		3	.4	.1	6.4	1.4	.5	.2	.1
2C	8.4	8.9			.1	.1	.1	9.3	1.2			1.5	.1	.1	8	2	.2		
2D	9	3		.1	.2	.4	3	6	1.2	.1	.1	4.6	.7	.8	3.7	.7	.1	.5	.1
2E	9.4	2.8			.1	.1	1.5	6.9	2	.1		1.4	.2	.1	7.8	2	.4		
2F	10	8.3					2.1	1.3	2.1	1.7		.4		.2	9.4	3.6			
2G	8.6	6.2			.4	.7	2.4	7	1.4			4.3	.3	.6	4.8	.7	.3	.1	.2
3A	.9	9.2				.3	8.6	3.8				2	.3		7.7	.9	1.3		
3B	1.1	9			.1	.6	9.4	1.8	.1	.1	.2	7.4	.2	.7	1.1				.1
3C	.4	9.7			.1	.4	4.2	7.3	.2			4.3	.1	.4	4.9	1.1	.1		
3D	.7	9.5					.9	8.7	2.5			1.5	.1	.1	8.1	1.1	.8		.1
5A	9.7	0.6		.1	.3	8.7	1.3	.2			.1	5.8	2	.1	1.9	.13		.1	.2
8	9.5	.2			.5	.2	5.9	5.5	.9	.9	.4	6.7	.6	1	1.9	.1	.6		.5
7E	1.5	8.9			.1	1.4	9.1	1.8				5	.4	.2	5	.6	.1		.1
7D	6.7	3.3			.1	7.9	4.9	1.2	.4			4.9	2.3	.5	1.4		1		.1
7C	5	5.2			1.3	3.7	5.5	1.5				5.8	1		1.7	.5		.4	.8

Numbers are average total thicknesses i 10 m samples

SANDSTONE SEDIMENTATION

Introduction

There is far more sandstone than any other type of sediment in the outcrops of the western margin. Our attempts to analyse these enormous amounts of relatively homogeneous sandstone rely very much on our method of multivariate analysis and classification. This method has been fully described in Number 1 of this volume of Meddelelser. The sample groups defined during this analysis and used in the classification are illustrated in the Introduction to this present Number (Figs. 4, 5, 6). At this stage we augment this illustrative material by presenting a table of the average features of each of the sample groups (Table 4). Full details of sedimentary structures and fossils and their distribution amongst the sample groups were presented in Number 2 of this volume of *Meddelelser om Grønland.*

Definition of fans and another river system

Introduction

Major conglomerate bodies that were probably formed by alluvial fans have been discussed in the section on "Conglomerates and the Unconformity". They are also indicated on Fig. 52. However, most of our research in Greenland was concerned with the sandstone lithologies. This first section is concerned with the definition of sandy fans by means of the analysis of palaeocurrents, and the characterisation of these fan sediment bodies in terms of detailed sediment types (sample groups).

The regional distribution of these features will be described in terms of three stratigraphic units, previously defined:

a) Lower Rødebjerg Formation

b) Upper Rødebjerg Formation

c) Sofia Sund Formation

Palaeocurrents

Palaeocurrent vectors for each locality have been worked out. From these, mean palaeocurrent vectors were calculated for each mountain. These are illustrated in Fig. 43. The essence of our analysis is the recognition of groups of neighbouring vectors that radiate out from relatively well-defined centres.

In the *Lower Rødebjerg Formation*, two groups of palaeocurrent vectors are found.

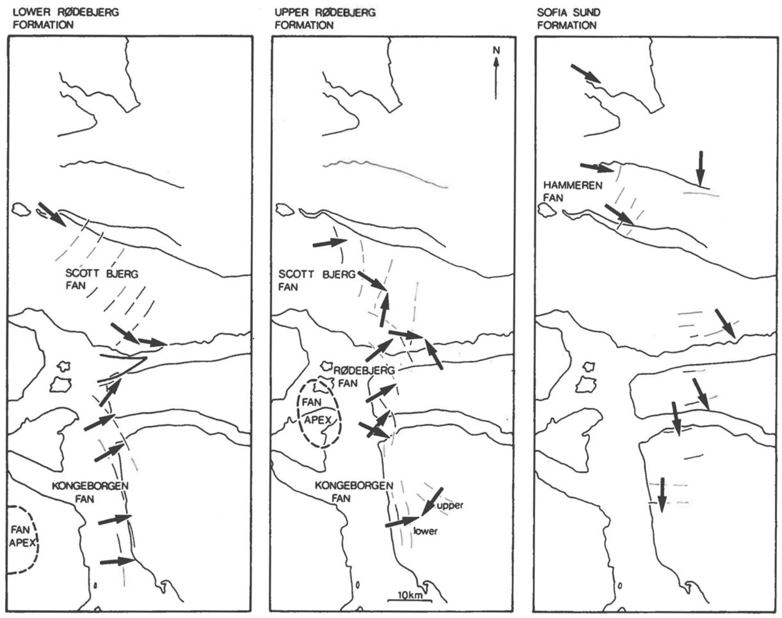

Fig. 43. Maps showing means of palaeocurrent vectors for the three stratigraphic units of the western sequence. The form of the proposed fans is shown by lines perpendicular to the vectors.

(a) Kongeborgen: The stratigraphic members (see Fig. 18) in this cluster are the Svedenborgs Bjerg green sandstone, Rebild green sandstone, Rebild green sandstone and conglomerate and Valley 'e' green sandstone members. The Southern Kongeborgen green, and green and red sandstone members show a similar palaeocurrent pattern but they are much lower in the stratigraphy and the facies are different from the rest of the unit. It is thought that these two members may be part of a separate system.

(b) Scott Bjerg: All the Scott Bjerg members above the red and green sandstone member, all the East Rødebjerg members except the red sandstone member and all the West Rødebjerg succession except the upper red and variegated sandstone members are included in this group. The palaeocurrent vectors in both groups trend to the east.

In the *Upper Rødebjerg Formation* there are still groups on Kongeborgen and Scott Bjerg and there is also a third group:

(c) Rødebjerg: This includes the East Rødebjerg red sandstone, West Rødebjerg red sandstone and variegated sandstone, Svedenborgs Bjerg red sandstone and white and red sandstone. Rebild red sandstone, and Valley 'e' red sandstone members. The palaeocurrents are to the east in this group as well.

There is a palaeocurrent reversal in the upper part of the Kongeborgen system at Valley 'e', which probably indicates that a new system was depositing sediment which had been derived from the northeast. There is no comparable palaeocurrent change in the Rødebjerg system.

In the *Sofia Sund Formation* there are two palaeocurrent vector groups:

(d) Hammeren: The palaeocurrents in all the members of Heintz Bjerg and Hammeren were transporting sediment to the east.

(e) Sofia Sund: All the other sections measured in the Sofia Sund Formation in this area have a southerly trend and are probably part of the same or similar systems.

The palaeocurrent vectors are grouped by their tendency to radiate from separate centres. The locations of some of these vector centres are shown in Fig. 43. These groups are used to define 'radial fans', and the vector points are regarded as 'fan apices'.

The Sofia Sund system is much larger than the fan systems and does not clearly radiate from any centre. It is referred to below as a non-radial fluvial system.

Downstream variation (parallel to the palaeocurrent vectors) is referred to as downstream change, and variation normal to the vectors is referred to as lateral change.

On Angelins Bjerg, in the Upper Rødebjerg Formation, all the red sandstone members have a northerly palaeocurrent and all the non-red members a southeasterly trend. We interpret this as the interfingering of the Scott Bjerg and Rødebjerg fans. The palaeocurrent pattern on Rødebjerg is confused, but there is both a northern and a less strong southern mode, and we interpret this also as the interfingering of the Rødebjerg and Scott Bjerg fans.

Distribution of sample groups

Although defined primarily by palaeocurrent patterns, the fans are locally distinguished by their detailed sedimentation features. The most abundant sample groups in each locality are shown in the north-south section of Fig. 44.

Lower Rødebjerg Formation. The most southerly outcrops of the Kongeborgen fan are of sample group 3D (grey-m.sst.-trough X), and to the north, that is laterally, 3C (grey-m.sst.-trough X), becomes dominant.

On the Scott Bjerg fan, sample groups in the lower 300–400 m reflect proximity to the unconformity, but above this the dominant sample group is 3D (grey-m.sst.-trough X). Lateral to this, at approximately the same stratigraphic height, on West Rødebjerg, there are sample groups 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X). Lower in

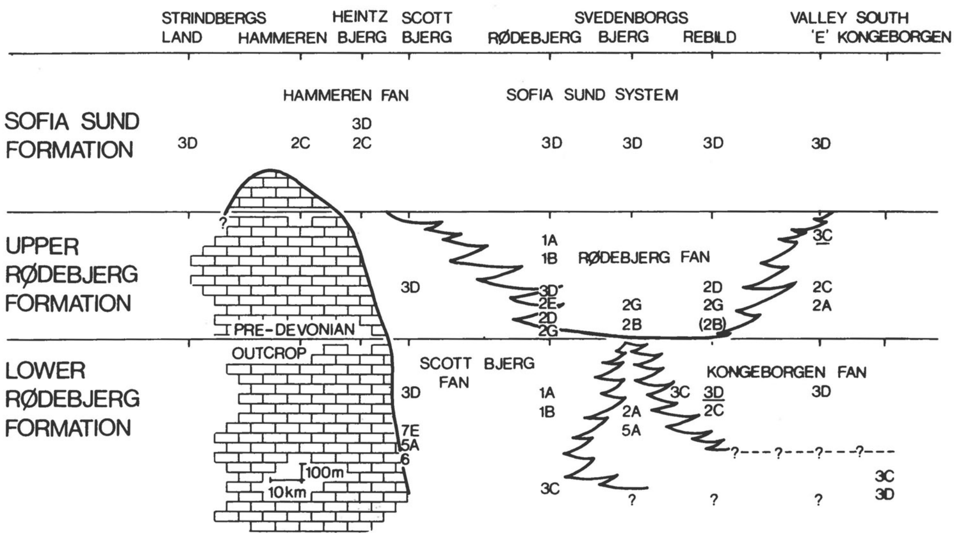

Fig. 44. Diagrammatic section, trending north-south and showing the fan bodies and their main constitutituent sample groups.

the stratigraphy on West Rødebjerg, 3C (grey-m.sst.-trough X) is dominant.

On northwest Svedenborgs Bjerg, the Scott Bjerg and Kongeborgen fans are separated by a distinctive area of 2A (red,grey-f.,m.sst.-trough X) with 5A (red-v.f.sst.-flat,asym.rip.). On the maps (e.g. Figs. 43, 45, etc.) this is shown as a distinctive triangular area of interfan sedimentation.

Upper Rødebjerg Formation. The Kongeborgen fan shows a change from the 3D (grey-m.sst.-trough X) characteristic of the previous stratigraphic unit, to 2C (red,grey-m.sst.-trough X) and 2A (red,grey-f.,m.sst.-trough X). After the palaeocurrent reversal, 3C (grey-m.sst.-trough X) becomes dominant.

The Rødebjerg fan is characterised by 2G (red-m.sst.-trough X,flat), 2D (red-m.sst.-trough X,flat) and 2B (red,grey-m.sst.-trough X) in the lower part of the successions, but 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X) become common higher up.

The Scott Bjerg fan is dominated by 3D (grey-m.sst.-trough X).

Sofia Sund Formation. The Sofia Sund system is dominated by 3D (grey-m.sst.-trough X).

The Hammeren fan is characterised by 2C (red, grey-m.sst.-trough X)

Univariate analysis of river systems

Having established the presence of the fans and the Sofia Sund system, we shall now examine the variation of certain sediment features within these river systems.

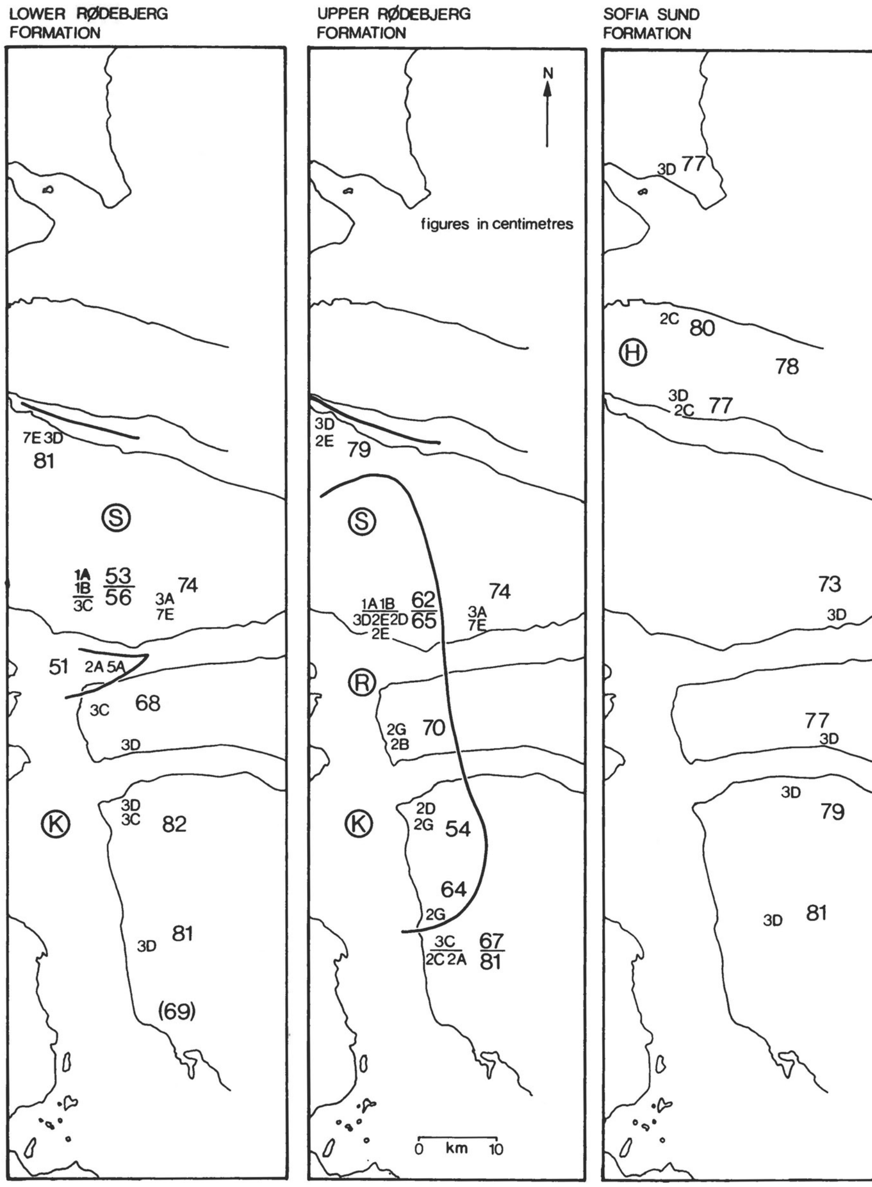

Fig. 45 Maps showing maximum set thickness for cross-bedding for localities in the three stratigraphic units of the western sequence. Numbers are thicknesses in centimetres. Most important sample groups are also shown. Ringed letters indicate fans: H, Hammeren; K, Kongeborgen; R, Rødebjerg; S, Scott Bjerg. Some fan edges indicated. Short horizontal lines between figures indicate upper and lower parts of local successions.

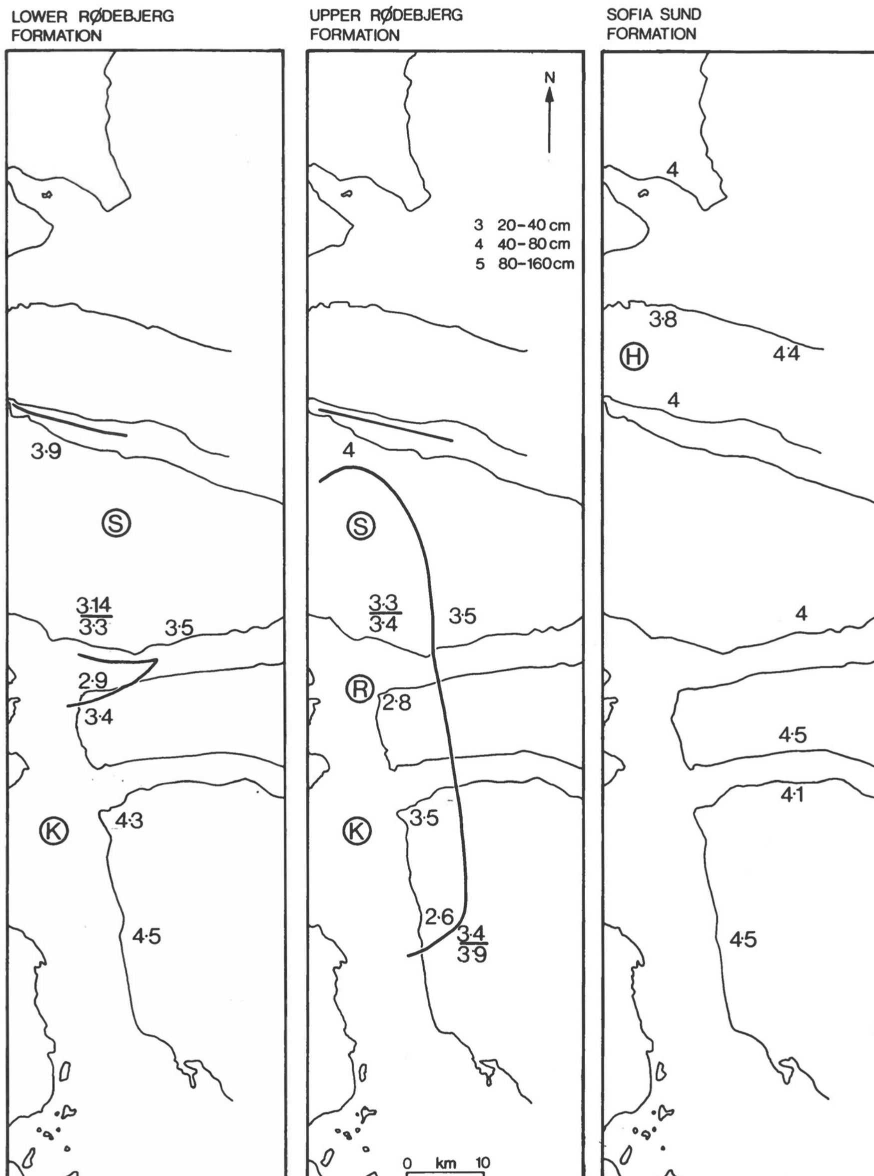

Fig. 46. Maps showing mean coset (same structure) thickness for cross-bedding for localities in the three stratigraphic units of the western sequence. Numbers are thicknesses expressed on an arbitrary scale in which thicknesses of 20–40 cm were scaled as 3, 40–80 cm were scaled as 4, 80–160 cm were scaled as 5. Other conventions described in caption of Fig. 45.

Fig. 47. Maps showing means of the maximum grain sizes of each 10 m sample in localities in the three stratigraphic units of the western sequence. Numbers are grain-sizes expressed as Ø units (0 to 1, coarse sand; 1 to 2, medium sand; 2 to 3, fine sand). Other conventions described in captions of Fig. 45.

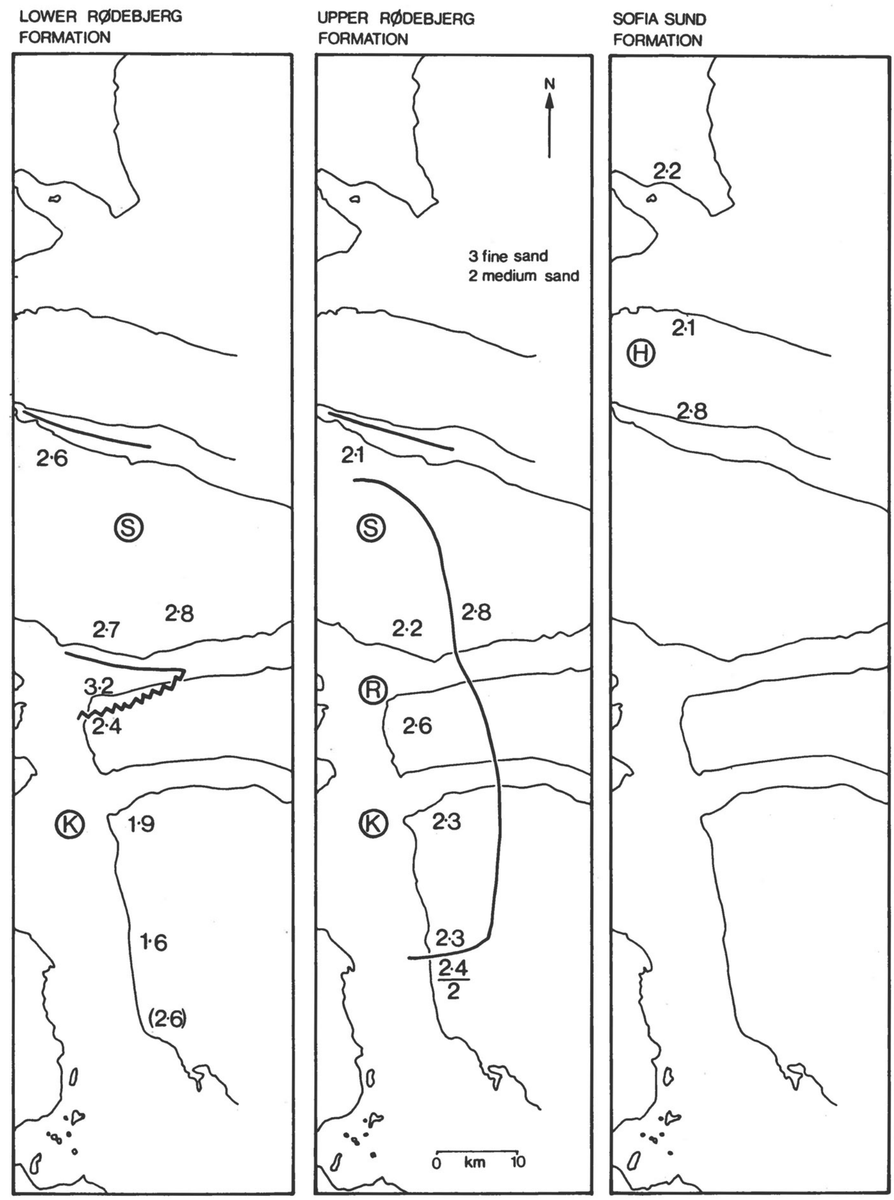

Fig. 48. Maps showing means of mean grain size (weighted by thickness) for each 10 m sample in localities in the three stratigraphic units of the western sequence. Numbers are grain-sizes expressed as Ø units (see Fig. 47). Other conventions described in captions of Fig. 45.

Bed thickness

Values for cross-bedding maximum set thickness per 10 m sample, and for mean coset thickness per 10 m sample, have been averaged for each locality, and plotted on Figs. 45 and 46.

Both these parameters show a tendency to decrease downstream and/or laterally in the various fans. In contrast the Sofia Sund system shows no perceptible trend. A case has been made for regarding both parameters as measures of alluvial depth. Set thickness may be related to flood depth during formation and movement of the sand megaripples in which the cross-stratification formed, and coset thickness may be related to bank-full depth or river-bar height. The downstream and lateral tendency to diminish therefore suggests a tendency for rivers to diminish in size downstream and laterally on the fans. No such tendency is apparent in the much larger Sofia Sund system.

Grain size

We have used two parameters to generalise grain size at the various localities. For each group of localities we present (Figs. 47 and 48) the average of the maximum grain size for each 10 m sample, and the average of the weighted mean grain size for each 10 m sample.

We find that, with one exception, the radial fans are characterised by decrease of grain size both downstream and laterally. The Sofia Sund system does not show any trend in grain size variation.

Our study of the western margin has shown us that this margin exhibits a relatively narrow strip of sediment, approximately normal in trend to the average of the palaeocurrents that deposited it. The fact that the fragments of fans that we have been able to recognise show down-current and lateral decrease in averaged grain sizes, leads us to ask why grain size should show a decrease downstream in a radial fan system.

There is no evidence in the literature that attrition of river sediment load (Leopold, Wolman & Miller, 1964, p. 90; Schumm, 1968, p. 16) significantly decreases particle size over the rather short distances we envisage in East Greenland.

A downstream decrease of grain size may be caused by the trapping of coarser particles in sedimentary structures upstream. Coarse particles have a tendency to lag on the upstream side of bed forms (Meland & Norrman, 1969, p. 142) and at the foot of the downstream slope. In Greenland, cross-bedding does not usually show this segregation of grain size. However, some other structures such as channel fills, and river bar sequences, do show a concentration of coarser particles in their lower parts.

The duration and the strength of a flood event in a river will affect the distance a particular sediment grade will be transported. For example, if there is just sufficient power to transport some coarse sand as bed-load, then a proportion of medium sand will be carried in suspension, and there will be a full suspended load of fine sand (BAGNOLD, 1966; SHIELDS, 1936). Suspended load will inevitably be transported more rapidly than bed-load. In a single flood event finer sediment will therefore move further down a fan slope, than coarser sediment.

We can summarise this by saying that the grain size of sediment deposited is likely to decrease partly because of trapping of coarser material in bed and channel forms, and partly because of the rapid downstream movement of finer, suspended load sediment. The rate of decrease of particle size would be greatest where high sediment accumulation rates discourage reworking, and where flood peaks are short and sharp, limiting the transport distance of the coarser grades.

Although in general the Greenland fan sandstones show this downstream tendency of finer mean grain size parameters, there are some situations where this tendency does not occur. The Kongeborgen fan at Rebild has a particularly high mean maximum grain size (Fig. 47.) We suggest that this may reflect the local presence of a distributary from the conglomerate fan on Ella Ø. The Sofia Sund system also does not show any tendency to be finer-grained downstream. Although stratigraphic control of section is poor, it is fairly certain that there are no systematic changes of this sort over the 100 km downstream distance from Strindbergs Land to Valley "e", on Kongeborgen. We think that this means that the critical flood strength for the movement of coarse sand must have been available for sufficient aggregate time to enable coarse sand to be transported at least 100 km, before it became permanently incorporated in the sedimentary succession. The details of sedimentary facies, including estimates of relative channel depths are the same on the Sofia Sund system as they are on the Kongeborgen fan. This implies that flood events must have lasted distinctly longer on the Sofia Sund fluvial system than they did on the marginal radial fans.

The grain size (weighted mean) and coset thickness (log of mean) for each locality vary together in a linear way (Fig. 49). Because we think that coset thickness is related to channel depth, this would imply some relationship between channel depth and grain size.

Because the silt and clay content of the various successions we have studied varies hardly at all (within the fans at least), we can assume that the width/depth ratio of the channels was more or less constant (SCHUMM, 1961; 1969, p. 258). The shallower channels must, therefore, have carried less water. Reasons why channel discharge might decrease downstream are:

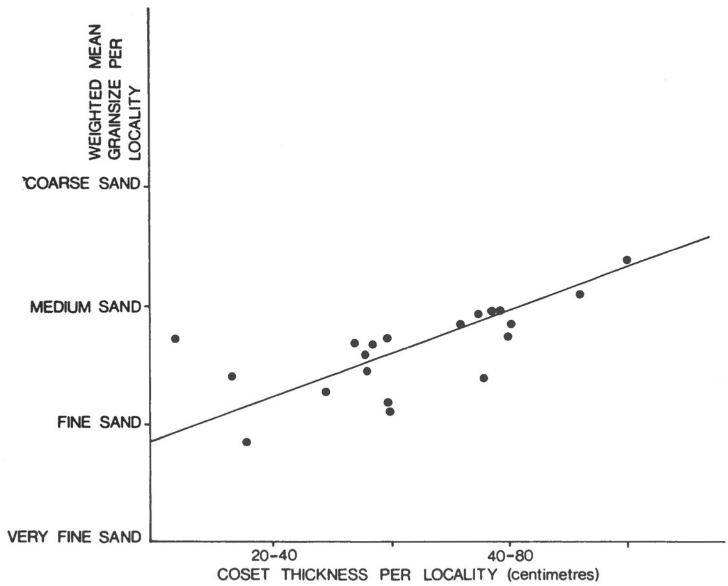

Fig. 49. Diagram showing relationship of mean grain-size per western sequence locality (weighted for thickness), and mean coset (same-structure) thickness for cross-bedding.

a) percolation into the fan sediment
b) evaporation
c) downstream branching of the channels.

Pebble content

Three main types of pebbles were recognised in the sandstones of the western sequence:

a) *limestones and dolostones*, from the Combro-Ordovician or from the Limestone-Dolomite Series of the Upper Eleonore Bay Group.

b) *vein quartz*, *quartzites*, *sandstones and siltstones*. The vein quartz probably came from source rocks stratigraphically below the Limestone and Dolomite Series of the Upper Eleonore Bay Group. The sandstone and siltstone may have been derived from the Cambro-Ordovician, or from the Upper Eleonore Bay Group.

c) *crystalline metamorphic clasts*. The commonest type is quartz schist, and gneissose pebbles were also found.

No obvious relationship exists between grain size and structures, on the one hand, and type of pebbles on the other. For example, sample group 3D (grey-m.sst.-trough X) contains the following different clast situations: Kongeborgen fan, full range of clast types: Scott Bjerg fan, only limestones and dolostones; Rødebjerg fan, normally no clasts at all.

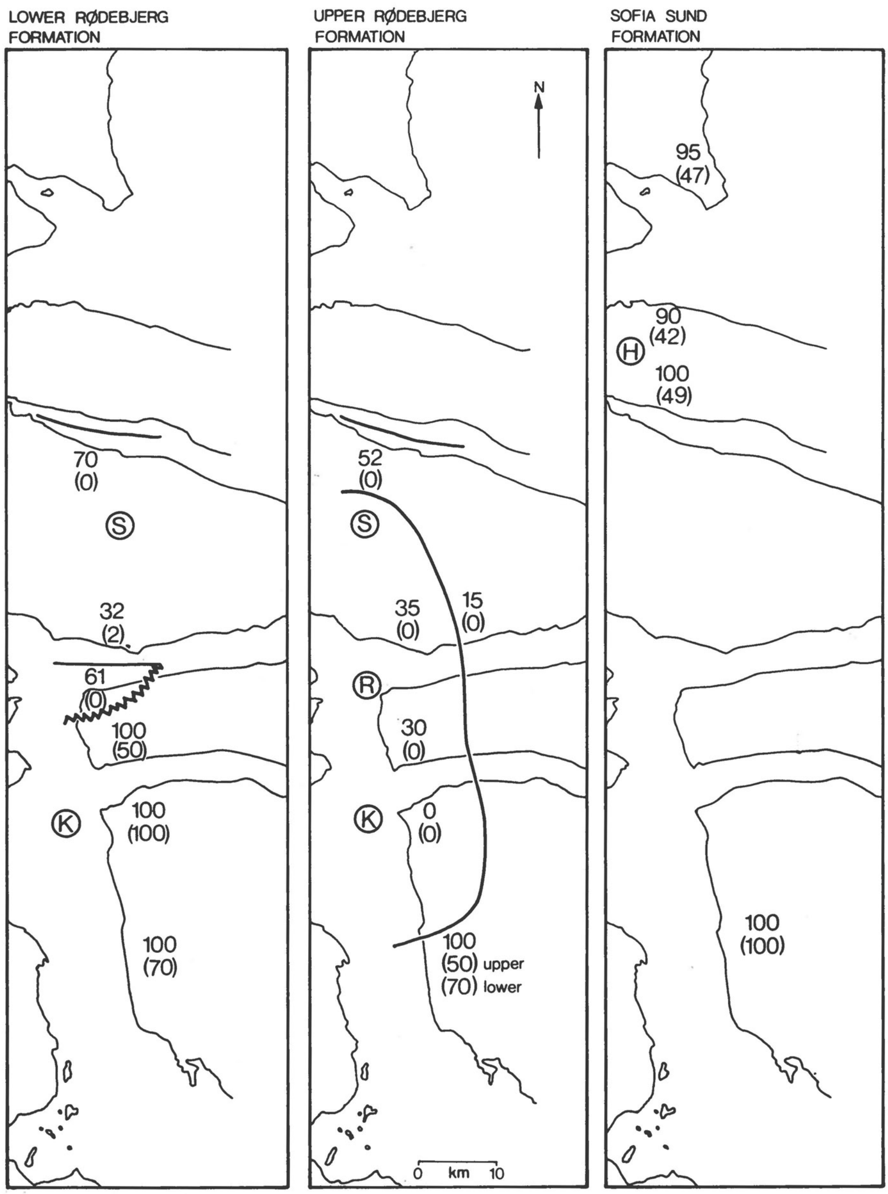

Fig. 50. Maps showing percentage of 10 m samples that contain extraclasts in localities in the three stratigraphic units of the western sequence. Percentage with metamorphic clasts is shown in brackets. Other conventions described in captions of Fig. 45.

Figs. 50 and 51 present our information on pebble content, and especially the distribution of crystalline metamorphic clasts. One feature that is remarkable about this distribution is the absence of crystalline metamorphic pebbles in the Scott Bjerg and Rødebjerg fans. We shall now discuss the possible significance of this.

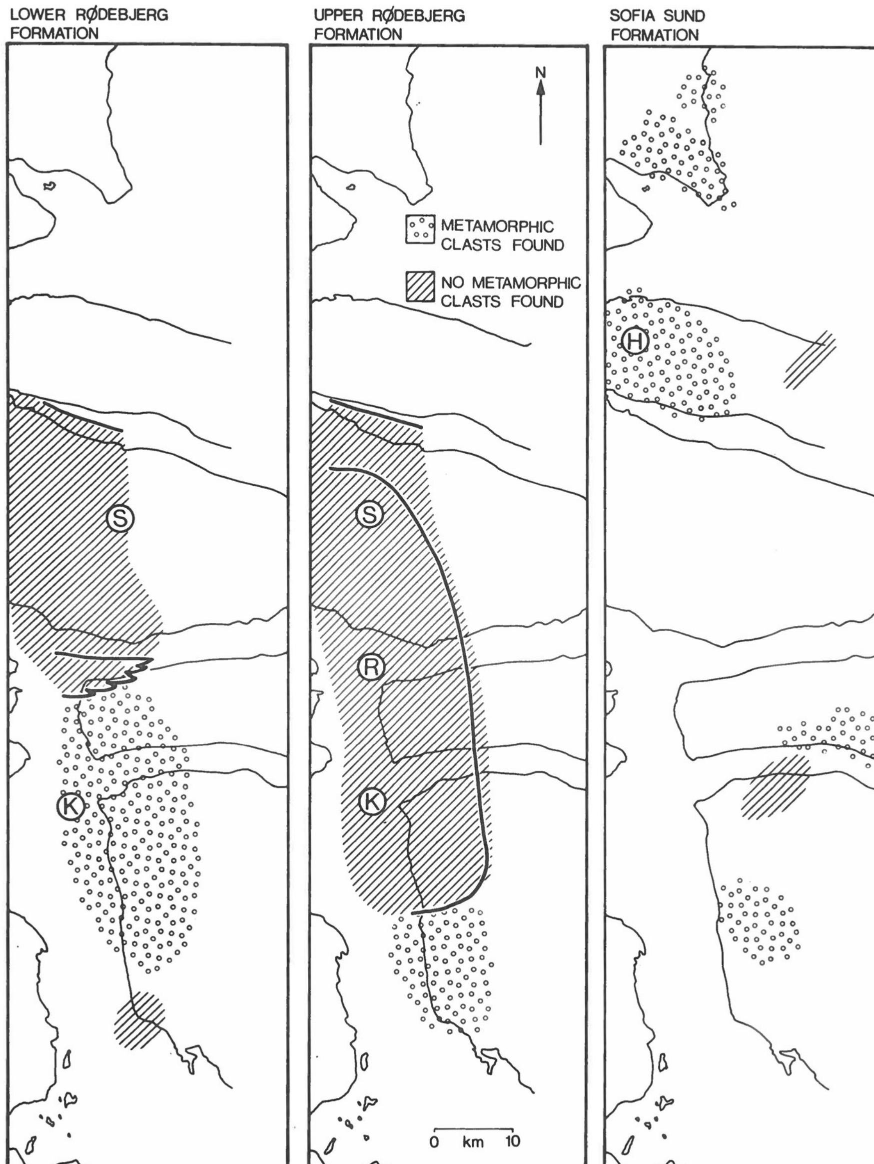

Fig. 51. Maps showing distribution of metamorphic clasts in the three stratigraphic units of the western sequence. Other conventions described in captions of Fig. 45.

We think it likely that all the fans had some metamorphic rocks outcropping in their source areas. One argument in favour of this concerns the Rødebjerg fan, whose fan apex was approximately in the area where the rather earlier Ella Ø conglomerate succession was very rich in metamorphics. If metamorphic source rocks were available in Ella Ø

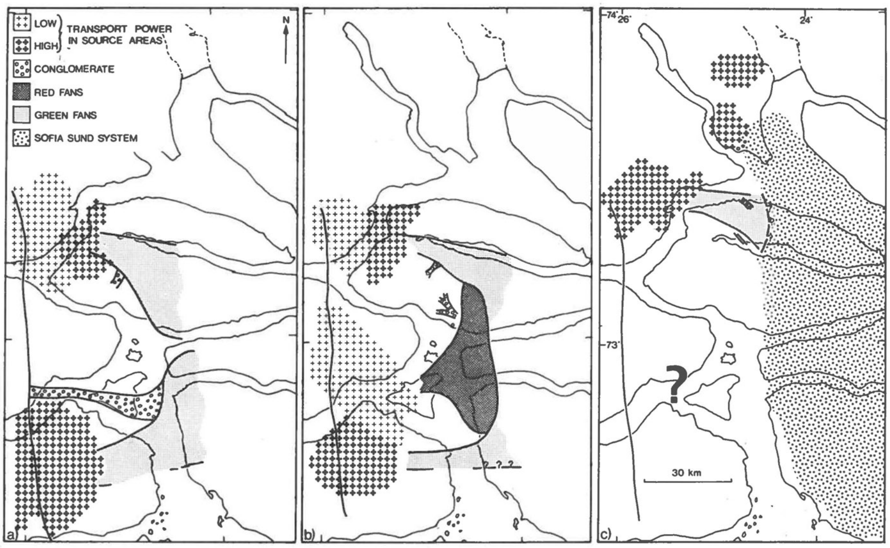

Fig. 52. Maps showing fans and source areas for three stratigraphic units of western sequence: a, Lower Rødebjerg; b, Upper Rødebjerg; c, Sofia Sund.

conglomerate times, we think they would probably still have been available in Rødebjerg fan times.

All sandstones of the fans contain abundant garnet, microcline, hornblende and plagioclase, as well as quartz showing undulose extinction and suturing. We think this is strong evidence for the presence of metamorphic source rocks.

We find no evidence, in the way of relict fragments, that metamorphic clasts were destroyed by weathering or transport in some of the areas.

We suggest that the most likely explanation involves factors in the source areas. Some areas, though exposing metamorphics, did not yield pebble-size metamorphic clasts to their alluvial accumulations, other areas did. This may reflect differences of river downcutting and local rates of crustal uplift. For example, some of the tributary rivers may have emerged through deep limestone gorges where river strength was so great that limestone detritus swamped that from other parts of the catchment.

Migration of river systems

The positions of the fans in the three formations are summarised in Fig. 52.

The Lower Rødebjerg—Upper Rødebjerg Formation boundary is marked by the appearance of a new sandstone fan that we call the Rødebjerg fan. Tectonic movements, change in rainfall pattern or even a river capture event may have initiated the growth of this new fan. To the north and south, the Scott Bjerg and Kongeborgen fans continued in existence across this stratigraphic boundary.

At the top of the Rødebjerg Formation, the Sofia Sund Formation is defined at a major change in the style of sedimentation:

a) the grain size increases everywhere
b) the palaeocurrent directions trend to the south rather than the east
c) samples become dominantly of group 3D (grey-m.sst.trough X)
d) metamorphic clasts become general
e) the fluvial system becomes non-radial

Many of these changes are clearly related to each other. One possible explanation is that they represent a basin-wide event which caused discharge from the west to cease, and initiated discharge from the north. Or we can imagine the changes in the sediments of the western margin resulting from the migration westwards into the area of a major southward flowing river system. We do not have enough regional spread of stratigraphic units to decide between these two concepts, but the latter one seems most likely to us because it is less catastrophic. It would imply that the Rødebjerg-Sofia Sund Formation boundary would be notably diachronous from east to west.

No Devonian sediment is found on Heintz Bjerg and Hammeren until, in Sofia Sund times, sediment accumulated from the southward flowing river system. This again is more readily understood in terms of the westward migration of the river system, in this case, covering the basement rocks. It is important to note that all the Rødebjerg Formation radial fans lie south of the Hammeren horst (Fig. 53). It is possible that this horst acted as a barrier and prevented the marginal fans from being reworked by the major southward flowing Sofia Sund system.

Multivariate analysis of river systems

Green sandstone fans form the great majority of all fluvial deposits on the Western margin. The Kongeborgen, Scott Bjerg and Hammeren fans are all green, as is the Sofla Sund system.

Very fine sandstone margins of green fans

Scott Bjerg. The situation where green fans have very fine sandstone margins, and are near the basal Devonian unconformity, has been studied at Scott Bjerg, Heintz Bjerg and Hammeren. The localities will be described in that order.

The stratigraphic relationships on Scott Bjerg between the conglomerate, and the red and green sandstone members are described in the

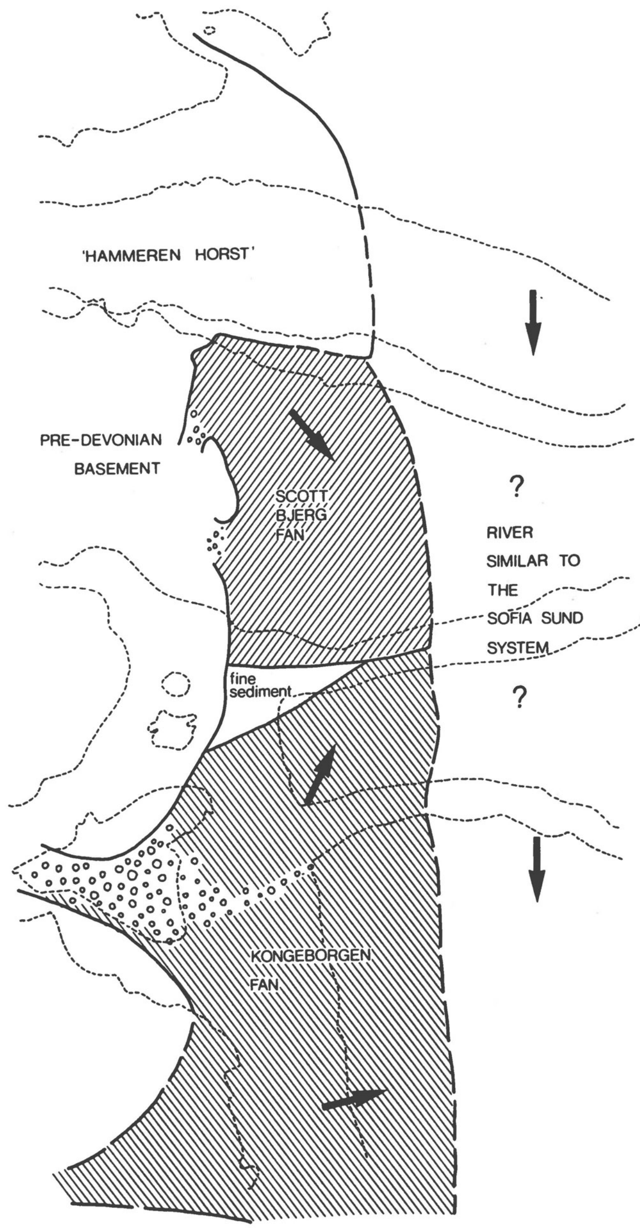

Fig. 53. Map illustrating presence of Hammeren horst and fans to the south in Lower Rødebjerg Formation times, in relation to predecessor of the Sofia Sund system further to the east.

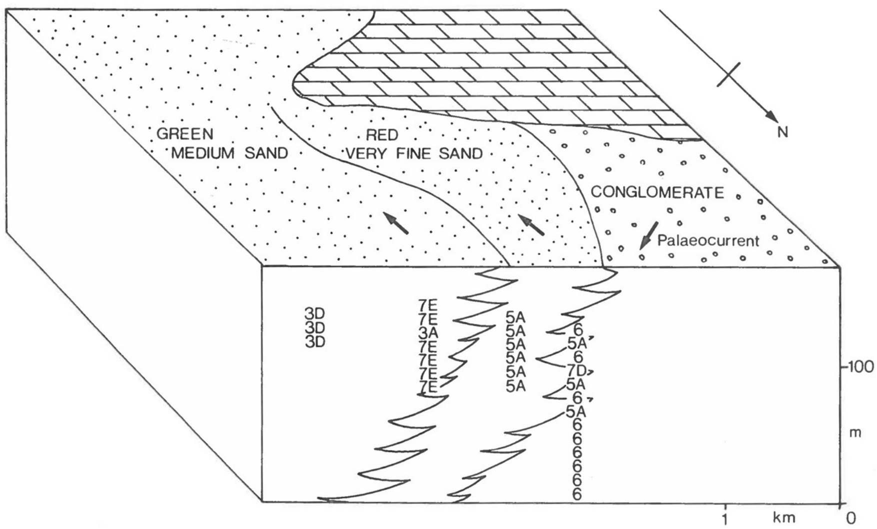

Fig. 54. Block diagram illustrating relationships between different sample groups as edge of Scott Bjerg fan, Scott Bjerg.

section on Stratigraphy and Structure, above. The sample groups which occur within these members are illustrated in Fig. 54 and Table 5.

At the base of the section, sample group 7D (grey-co.sst.-trough X), 5A (red-v.f.sst.-flat,asym.rip.) and 6 (congl.) occur. Sample group 7D (grey-co.sst.-trough X) is something of a dustbin. In this case, it is very similar to 5A (red-v.f.sst.-flat,asym.rip.) but contains about 1 m of trough cross-bedding. Low in the section, two 50 cm conglomerate bands occur, and three units (0.1–2 m thick) of green fine-grained sandstone with trough cross-bedded sets, were present in 50 m of section. The conglomerate becomes very rare higher in the succession, which ultimately consists entirely of sample group 5A (red-v.f.sst.-flat,asym.rip.). The palaeocurrent direction, based on measurements of trough cross-bedding, is southwards and southeastwards in contrast to the easterly flow indicated in the conglomerate.

In the red and green sandstone member, horizons of green sandstone are interbedded with units of red sandstone. The thickness of these units is of the order of 10 m, therefore a 5 m rather than a 10 m classification interval is more informative (Table 5). The occurrence of 1A (red-f.sst.-flat), 1B (red-f.sst.-trough X) and 1D (grey-f.sst.-flat,trough X) shows that the red units are coarser than in 5A (red-v.f.sst.-flat,asym. rip.).

The palaeocurrent directions in the green sandstone and the red and green sandstone members, and in all the red fine-grained units of the conglomerate and red sandstone member, are to the east-south-east. This trend roughly parallels the junction between those stratigraphic

Table 5. *Scott Bjerg sequence*

top of section		follows below		follows below	
(10 m)	(5 m)	(10 m)	(5 m)	(10 m)	(5 m)
3D		5A	5A	5A	5A
3D			5A		5A
3D					
		5A	5A	6	6
20 m gap			5A		6
7E	7E	5A	5A	5A	1C
			5A		5A
7E	7E				
	1D	5A	5A	6	5A
			5A		6
3A	1B				
	7E	5A	5A	6	6
			5A		6
7E	7E				
	7E	20 m gap		6	6
					5A
7E	1A	6	7B		
	7C		6	6	6
					6
7E	7D	5A	5A		
	7E		8	6	6
					6
7D	7B	6	6		
	7D		7D	6	6
					6
10 m gap		7D	5A		
			7D		
5A	5A			unconformity at base of	
	5A	10 m gap		section	

members (Fig. 54). Therefore the changes in sample group from one member to another are lateral to the main palaeoslope.

The difference in lithology and palaeocurrent directions between rocks in sample group 6 (congl.) and 7E (grey-f.,m.sst.-flat,trough X) suggests that these were deposited in separate fluvial systems. Sample group 5A (red-v.f.sst.-flat,asym.rip.) is interbedded with both these sample groups and, therefore, may have been deposited by either of these systems or by another.

Our attempts to find out whether the fine-grained sediment came from the conglomerate system, or from the green sandstone system, have been inconclusive. Garnet and epidote are typical of thin sections of the green sandstones, but were not found in thin sections from the fine-grained sediments or from the matrix of the conglomerate. However they may be absent in these sediments because of the finer grain sizes involved. The rare palaeocurrent indicators in the fine-grained sediments, 5A (red-v.f.sst.-flat,asym.rip.), parallel those of the edge of the green sandstone, and are at about 70° to those of the conglomerate, but this does not help us to determine derivation. A plot (Fig. 55) of the lateral

Table 6. *Heintz Bjerg sequence*

north-east (K530) (K529)	(K528)	south-west (K527)
8		
1A		
8		5A
1A	8	5A
	7D	6
	5A	6
		6

variation of certain properties shows a simple trend from 3D (grey-m.sst.-trough X) through 7E (grey-f.,m.sst.-flat,trough X) to 5A (red-v.f.sst.-flat,asym.rip.) but this indicates the gradualness of change rather than derivation.

In summary the following sequence of sample groups is characteristic of the margin of the green fan on Scott Bjerg: 3D (grey-m.sst.-trough X) – 7E (grey-f.,m.sst.-flat,trough X) – 5A (red-v.f.sst.-flat,asym.rip.).

Heintz Bjerg. Here a rather similar pattern was found. Three sections were measured a distance of 40 m apart. Their sample groups are summarised (Table 6) in stratigraphic order.

Section K527 is similar to the Scott Bjerg conglomerate and red sandstone member. Only one unit of conglomerate is common to both K527 and K528, all the others wedge out northwards.

The trends of lateral variation are similar to those seen on Scott Bjerg. The transition from 5A (red-v.f.sst.-flat,asym.rip.) to 8 (red-v.f.sst.-flat) to 1A (red-f.sst.-flat) is of great interest. 8 (red-v.f.sst.-flat) is very similar to 5A (red-v.f.sst.-flat,asym.rip.) but contains more trough cross-bedding, and 1A (red-f.sst.-flat) contains fine sandstone with flat bedding and some medium to coarse sandstone with trough cross-bedding, which includes clasts of pink and red quartz, black limestone and dolostone which are not found in the breccia, suggesting the influence of another system laterally.

Above this outcrop, the exposure is poor for 20 m, but the section passes up into a green and red sandstone member, and then a green sandstone member. It is not possible to deduce the lateral relationship between the green sandstone, red and green sandstone, and conglomerate members at this locality. However slightly to the north of this area, there is a sequence containing eleven different red units and this passes further north into a sequence with eight red units. 400 m to the north these red units appear to pass into a green sandstone.

The sample groups in the succession are summarised in Tables 6

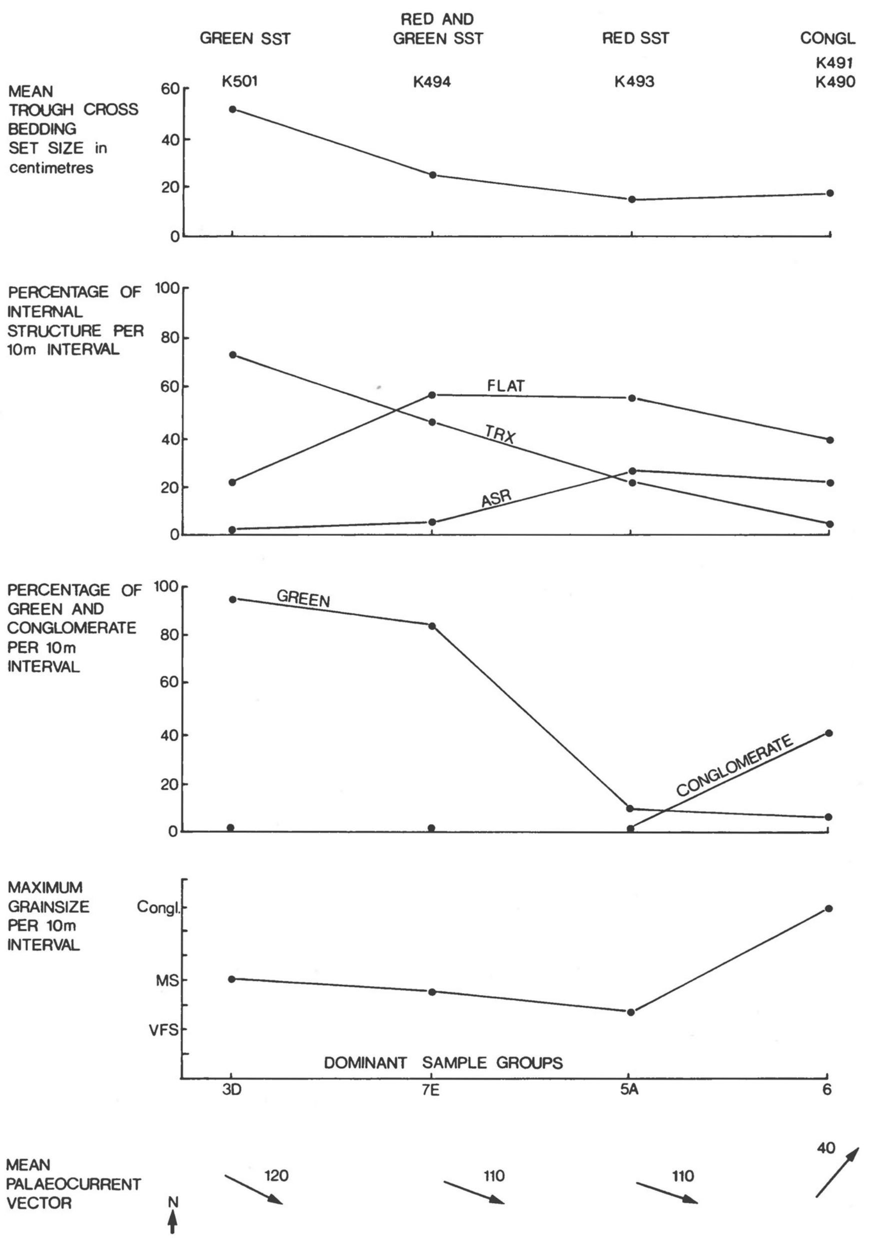

Fig. 55. Diagram to illustrate change of certain properties on Scott Bjerg, in lateral transition from sample group 3D to 7E, to 5A and to 6. Properties plotted are cross-bedding set thickness, percentage of various internal structures, percentage of green sediment and of conglomerate, maximum grain-size and palaeocurrent.

Table 7. *The variation of properties per 10 m sample in the lower part of the green sandstone, and red and green sandstone members on Heintz Bjerg*

Sample group 10 m	Sample group 5 m	Percentage green	Percentage trough cross-bedding	Percentage flat	Palaeocurrent direction
2C	2A 2C	100	84	7	92
3D	3D 2C	96	88	12	
2C	2C 2C	98	64	26	
2C	2C 2C	100	97	4	117
2A	2C 3A	98	71	26	
3A	3A 3A	100	75	18	
7E	3A 7E	100	64	22	
1A	3B 2A	57	31	43	119
3C	2A 3D	82	48	49	
3D	3D 3D	97	62	32	
1A	8 1A	22	1	59	

and 7. In the green and red sandstone member, they are similar to those in the Scott Bjerg green and red sandstone member and it is reasonable to assume that the two members were formed in similar sedimentary environments. At the base of the green sandstone member, the red band of 1A (red-f.sst.-flat) is followed by 7E (grey-f.,m.sst.-flat,trough X) and then a slightly coarser facies with more cross-bedding, 3A (grey-f., m.sst.-trough X). This is similar to the Scott Bjerg green sandstone member.

From the sample group properties, it can be seen that 2C (red, grey-m.sst.-trough X) and 3D (grey-m.sst.-trough X) are very similar but that the former contains more red colouration. A general pinkness apparent in the field is due to high concentration of pink feldspar. Otherwise the two sample groups seem similar.

Sample group 2A (red, grey-f.,m.sst.-trough X) is intermediate between 2C (red, grey-m.sst.-trough X) and 3A (grey-f.,m.sst.-trough X).

Table 8. *Hammeren sequence*

top of section 10 m	5 m	follows below 10 m	5 m
2C	2C	2C	2A
	2C		2C
2B	2C	2G	2G
	2B		8
2B	2B	2A	2A
	2C		2G
2C	3D	2G	2G
	2C		2C
2C	2C	2G	2G
	2C		2C
		(10 m gap)	
2C	2C	1A	1A
	2C		1A
2C	2C	1D	1D
	2C		1C
(10 m gap)			
2C	2C	6	6
	2C		5A
(10 m gap)		6	6
			6
2G	2G	6	6
	2G		6
		unconformity at base of section	

We feel sure that these vertical transitions also imply lateral association, and a sequence across the margin of the fan on west Heintz Bjerg would therefore be:

3C → 2A → 3A → 7E → 1A → 8 → 5A → 6
2C 3D 3C

Though showing more intermediate types, this is fully consistent with the lateral association described on Scott Bjerg.

Hammeren. A sample group succession through the stratigraphy of Hammeren is shown in Table 8. Three sections, K592, 591 and (Table 8) 581 are all at approximately the same level in the stratigraphy, and a line connecting the positions of the three lies more or less perpendicular to the general palaeocurrent direction. Table 9 summarises the lateral relations of the various sample groups.

At section K592, the outcrop is pale pink, and it includes a sample group not previously recorded, 2G (red-m.sst.-trough X, flat). We

Table 9. *The variation of sample groups and properties per 10 m interval near the base of the succession on Hammeren*

East section	K583	K592 Red	K592 Green	West K591
	2C	2G	3C	7D
	2B	2C	3D	1A
	2B	2G	3C	
	2C	1A	7C	
	2C	2G	3D	
	2C	2G	3C	

wondered whether this sample might be a reddened version of some of the green samples normally seen in a similar position on a fan margin. We therefore reclassified the 10 m samples of group 2G replacing the red characteristic with green. 2G (red-m.sst.-trough X, flat) then became either 3C (grey-m.sst.-trough X) or 3D (grey-m.sst.-trough X). Making this substitution, the Hammeren lateral sequence becomes similar to that seen on Scott Bjerg.

One difference between the Hammeren sequences, on the one hand, and those of Scott and Heintz Bjergs, on the other, is the lack of sample group 5A (red-v.f.sst.-flat,asym.rip.) and 1A (red-f.sst.-flat). We think it possible that the redness of sample group 2G (red-m.sst.-trough X,flat) may be related to its proximity to the unconformity and the conglomerate, perhaps reflecting greater diagenesis due to high intergranular water flow at the margin of the basin fill.

Svedenborgs Bjerg. Here there is evidence for a fine-grained fan margin, but no evidence for the proximity of the basal unconformity. The stratigraphy and structure of Svedenborgs Bjerg is complex and there is some doubt that our interpretation is correct. However assuming that it is, a sedimentological section is presented in Fig. 56. Because the palaeocurrent directions are approximately normal to this section, the logged successions are lateral equivalents. Mean values for internal structure, colour and grain size for the various locations on this mountain are plotted (Fig. 57).

At levels 2 and 3 (Fig. 56), the modal sample group 3D (grey-m.sst.-trough X) changes laterally to 3C (grey-m.sst.-trough X) and then to 2A (red, grey-f.,m.sst.-trough X). This is very similar to the lateral sequence observed on Scott and Heintz Bjergs where fan margins adjoin conglomerate members of the unconformity. We therefore suggest that the Svedenborgs Bjerg green sandstone member is at the northern edge of the fan, the Kongeborgen fan.

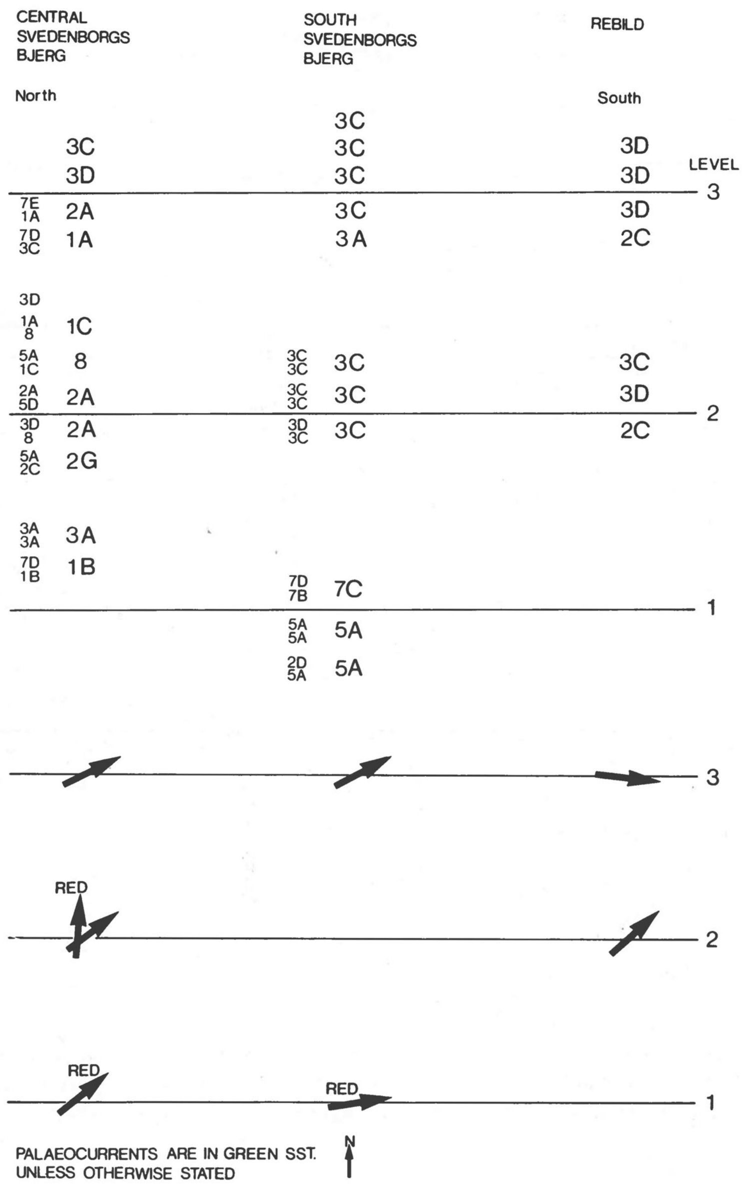

Fig. 56. Sample group successions and palaeocurrents in two sections on Svedenborgs Bjerg and one section on Rebild. The sections are placed in their suggested correlation positions. 10 m samples are in large numbers and letters; 5 m samples are in small numbers and letters.

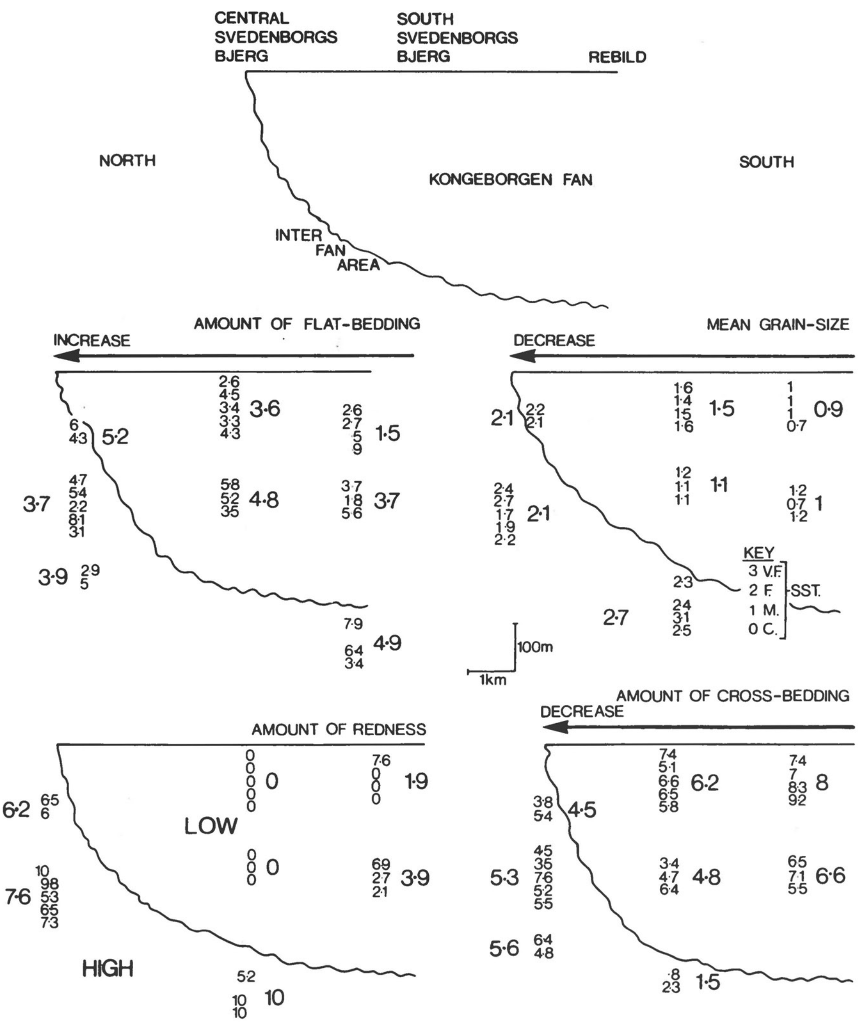

Fig. 57. Mean valves for certain properties of samples in three sections depicted on Fig. 56. All properties are thicknesses (m) of 10 m samples, except grain-size which is in Ø units. Curved lines running across diagrams indicate edge of Kongeborgen fan.

The interbedding of green and red sandstone at level 2 is best understood using a 5 m sample interval. In the two red units, the sequence of 5A (red-v.f.sst.-flat,asym.rip.), 8 (red-v.f.sst.-flat), 1A (red-f.sst.-flat) occurs, and the red units are separated by green units of 3D (grey-m.sst.-trough X) and 2A (red, grey-f.,m.sst.-trough X). The only sample group not previously described is 1C (red-f.sst.-flat,trough X) which is a redder, finer-grained version of 2A (red, grey-f.,m.sst.-trough X). By analogy with Scott Bjerg we regard 5A (red-v.f.sst.-flat,asym.

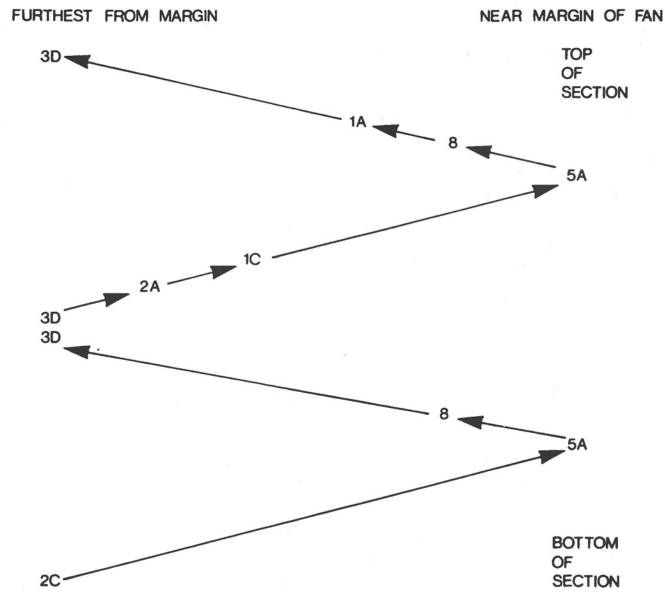

Fig. 58. Graphical representation of typical sequence of sample groups at margin of Kongeborgen fan, on Svedenborgs Bjerg and Rebild, plotted to show oscillation of fan margin.

rip.) as an indicator of the most marginal environments of sedimentation. Fig. 58 presents an analysis of the vertical sequence in terms of varying proximity to the fan margin.

Higher in the section (Fig. 56, level 3), the red units are interbedded with 3C (grey-m.sst.-trough X) and 7E (grey-f.,m.sst.-flat,trough X).

No sections were logged north of the central valley of Svedenborgs Bjerg, but in this direction we saw no green units in the green and red sandstone member and we suppose that the sediments are of sample groups 8 (red-v.f.sst.-flat) and 5A (red-v.f.sst.-flat,asym.rip.). On north-west Svedenborgs Bjerg, occur the outcrops of 2A (red, grey-f.,m.sst.-trough X) and 5A (red-v.f.sst.flat,asym.rip.) that we have already interpreted as the sediments of the interfan area.

The palaeocurrents measured for the red beds at level 1 (Fig. 56) are approximately parallel to green members at levels 2 and 3. However in the most northerly section at level 2, there is a distinctly bimodal distribution of palaeocurrents, the red samples trending more northerly than the green. This suggests that the red beds may have been derived from green rivers to the south, and thin sections show no significant detrital difference between the two lithologies.

The green and red sandstone member contains 'cycles' (cf Allen, 1965; Friend, 1966; Allen & Friend, 1968). To avoid confusion with the cycles and semicycles described in Alexander-Marrack et al (1970), we have named these larger units 'megacycles'. These megacycles have a green medium sandstone base and a red fine or very fine sandstone upper portion. They seem to be characteristic of fan margins in East Greenland.

Other localities with green and red megacycles. In southwestern Strindbergs Land, our section contains eleven or twelve red bands about 10 m–20 m thick interbedded with green sandstone. A section through one of these bands is as follows:

		5 m	10 m
		3D	3D
	Green	3C	
	Red	5A	2A
		2A	
Megacycle			
		3D	3D
	Green	3D	
	Red	2A	3C
Megacycle			
	Green	3C	

Sample group 2A (red, grey-f.,m.sst.-trough X) is a mixture of 3C (grey-m.sst.-trough X) and 5A (red-v.f.sst.-flat,asym.rip.). The association of 5A (red-v.f.sst.-flat,asym.rip.), 2A (red, grey-f.,m.sst.-trough X), 3C (grey-m.sst.-trough X) and 3D (grey-m.sst.-trough X) is similar to that seen on Svedenborgs Bjerg.

On East Rødebjerg, we saw three red units; a sequence of sample groups through one is as follows:

		5 m	10 m
		1D	3A
	Green		
		3A	
Megacycle	Red	7D	7C
	Green	7A	

The sample group 7C (grey, red-f.,v.f.sst.-flat) was found in the South Svedenborgs red silt member and this association is similar to one that could be predicted from the Svedenborgs Bjerg succession.

In *Valley 'e'* (*Kongeborgen*), at an altitude of 410 m, there are a 2 m red band and two thinner ones. The sample succession is as follows:

		5 m	10 m
		3D	
	Green		3D
		3D	
Megacycle	Red	2A	
	Green	3D	3D

This is similar to the succession on Strindbergs Land.

All the red horizons noted above are extensive over outcrops more than 100 m wide. No local evidence for the lateral equivalence of these samples nor for their situation on a fan can be obtained, but the vertical successions are similar to the red and green sandstone members of Svedenborgs, Scott, and Heintz Bjergs and all these are found near the margins of fans. One can postulate therefore that these locations were also close to fan margins.

Another possibly marginal situation was studied at the top of the Kap Kolthoff Supergroup on Hammeren.

The upper part of the Hammeren green sandstone member passes transitionally into the Kap Graah Group and a section (K587) was logged in this transition. The following succession of samples was obtained:

		5 m	10 m
		4D	
	Limestone		4D
		4D	
		7D	
Megacycle			7D
	Red	5A	
		2C	3D
		3D	
	Green	3D	3D
		3D	

In the highest part of the Hammeren succession many red bands are found. The sample relationships in the lowest of these are described below.

Sample group 3D (grey-m.sst.-trough X) and 2C (red, grey-m.sst.-trough X) make up the lowest 20 m of this succession but above this is a

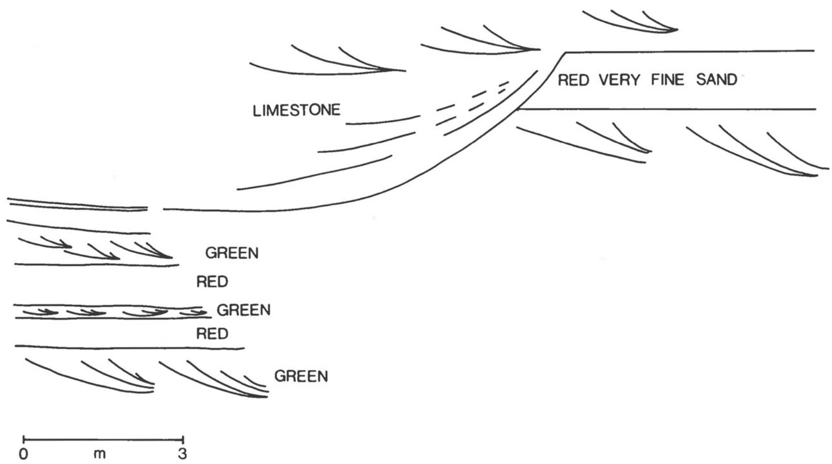

Fig. 59. Field sketch of succession including lenticular limestone at (K587) at top of Kap Kolthoff Supergroup on Hammeren.

sequence of samples that has not been described elsewhere. Sample group 5A (red-v.f.sst.-flat,asym.rip.) is the same us usual, but 7D (grey co.sst.-trough X) consists of large trough-cross bedded sets of medium-grained green sandstone interbedded with red flat bedded very fine sand. Overlying this is a 10 m thickness of black limestone 4D (grey-co.,m. slst.-flat) with a strongly discordant basal scour (Fig. 59). The limestone is partly finely laminated and partly in beds of about 5 cm thickness. Abundant carbonaceous plant material is present, and spores of the *Apiculatisporites* type have been recognised after treatment (K. C. ALLEN, personal communication). The base of the limestone body is cut into the following succession:

5 m	10 m
1D	2A
2A	2A
3D	

Sample group 2A (red, grey-f.,m.sst.-trough X) and 1D (grey-f.sst.-flat,trough X) are described in more detail in the West Rødebjerg upper red sandstone member (the red fan), but they consist of trough cross-bedded units followed by lenses of asymmetrically rippled red very fine-grained sandstone, containing rootlets and calcareous concretions. The trough cross-bedded cosets were deposited by the movement of dunes along the channel, and the finer-grained sandstones probably accumulated at lower stage.

Summary. We shall now generalise and compare the sequences of sediment accumulations that we have found in the various localities. We have repeatedly found a range of sample groups that we think were formed between fan centre and fan margin. Though the exact intermediates vary considerably the general range extends from 3D (grey-m.sst.-trough X) or (2C red, grey-m.sst.-trough X) to 5A (red-v.f.sst.-flat, asym.rip.).

We can examine this sequence in greater detail by dividing the fan margin into four parts:

(a) Green sandstone
(b) Red and green sandstone
(c) Red very-fine sandstone
(d) Conglomerate

The following sample groups are the most abundant in each of the four subdivisions (dominant groups are in italics):

(a) *2C* (*red*, grey-*m.sst.-trough X*), 3C (grey-m.sst.-trough X), *3D (grey-m.sst.-trough X)*.

(b) 1A (red-f.sst.-flat), 2A (red, grey-f.,m.sst.-trough X), 2C (red, grey-m.sst.-trough X), 3A (grey-f.,m.sst.-trough X), *3D* (grey-*m.sst.-trough X*), 7D (grey-co.sst.-trough X), *7E (grey-f.,m.sst.-flat,trough X)*.

(c) *5A (red-v.f.sst.-flat,asym.rip.)*, 7D (grey-co.sst.-trough X), 8 (red-v.f. sst.-flat).

(d) *5A (red-v.f.sst.-flat,asym.rip.)*, 6 (*congl.*).

The total number of transitions between samples was counted and the most frequent transitions are summarized below:

3D → 3C → 3A → 7E → 1A → 8 → 5A → 6
↑ ↓ ↓
2A 7D 7D

This sequence can be compared with those deduced for the various localities visited:

(a) *Scott Bjerg*

3D (grey-m.sst.-trough X) → 3C (grey-m.sst.-trough X) → 7E (grey-f.,m.sst.-flat,trough X) → 5A (red-v.f.sst.-flat,asym.rip.) → 6 (congl.).

(b) *Heintz Bjerg*

3D (grey-m.sst.-trough X) → 3A (grey-f.,m.sst.-trough X) → 2A (red, grey-f.,m.sst.-trough X) → 7E (grey-f.,m.sst.-flat,trough X) → 1A (red-f.sst.-flat) → 8 (red-v.f.sst.-flat).

(c) *Hammeren*

2G (red-m.sst.-trough X, flat) 3D (grey-m.sst.-trough X) → 3C (grey-m.sst.-trough X) → 1A (red-f.sst.-flat) → 6 (congl.).

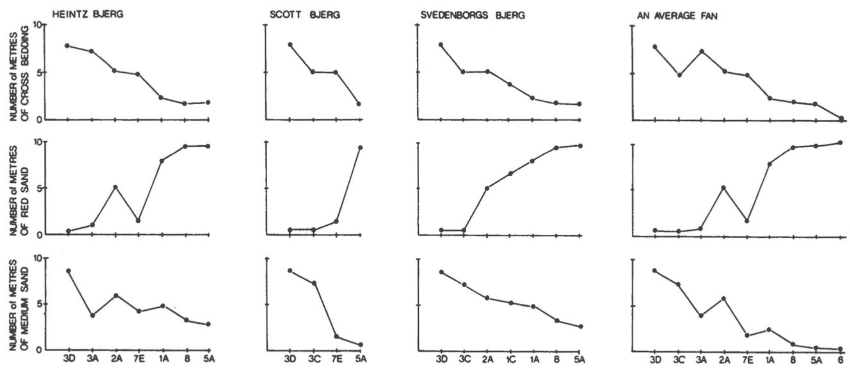

Fig. 60. Variation in properties of different sample groups in lateral sequence from centre to margin of various fans. Sequences on Heintz, Scott and Svedenborgs Bjerg are compared with a hypothetical 'average' fan.

(d) *Svedenborgs Bjerg*

3D (grey-m.sst.-trough X) → 3C (grey-m.sst.-trogh X) 2A (red, grey-f.,m.sst.trough X) → 1C (red-f.sst.-flat,trough X) → 1A (red-f.sst.-flat) → 8 (red.v.f.sst.-flat) → 5A (red-v.f.sst.-flat,asym.rip.).

The correspondence between the various localities is good. It must be emphasized that there is not a single simple sequence of samples at a fan margin. Considering the mean properties of the sample groups, it can be seen that there is a decrease in the thickness of trough cross-bedding and medium sand, and an increase in the amount of flat-bedding and red sandstone in passing towards the margin of the fan. (Fig. 60).

Coarser sandstone fan margin

A coarser sandstone margin of a fan is seen on Rødebjerg and Angelins Bjerg.

Western Rødebjerg. The exposure on this mountain is very good and 300 m was logged, but it was not possible to find the lateral relationships between successions, as was done on other mountains. The section was divided into four members:

Base of succession

(i) green sandstone member

(ii) green and red sandstone member

(iii) lower red sandstone member

(iv) white sandstone member

Top of succession

In fans with very fine-grained sandstone margins it has just been noted that 'megacycles', whose thickness is greater than 20 m, are easily

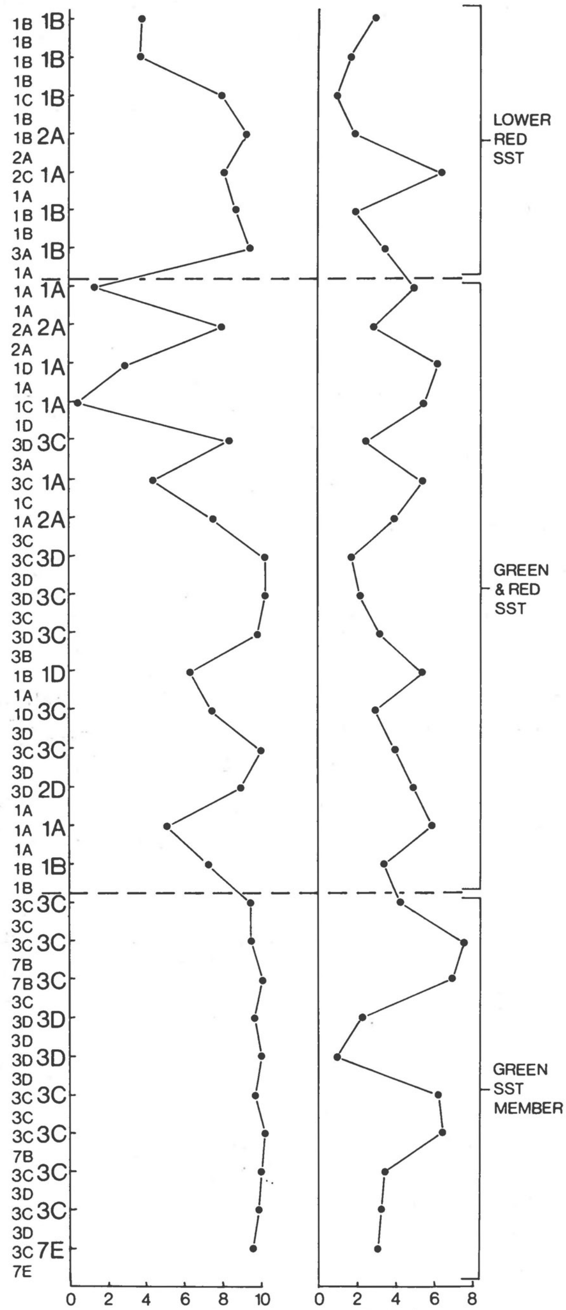

Fig. 61. Succession measured on West Rødebjerg. 5 and 10 m samples are shown classified. Propertion of 10 m units composed of green sediment and of flat bedded sediment are also shown.

observed. There is similar vertical variation in the rocks that formed the coarser sand margin to this fan and also in those that formed the centre of the fan. Megacycles ranging from 20 m to 100 m thick are found in which the amount of flat-bedding increases towards the top and the mean grain size usually decreases.

Three sample groups (Fig. 61) are represented in the green sandstone members; 3D (grey-m.sst.-trough X), 3C (grey-m.sst.-trough X) and 7E (grey-f.,m.sst.-flat,trough X) and this combination is found on Scott Bjerg and Heintz Bjerg, where they form a lateral transition towards the margin of the fan from 3D (grey-m.sst.-trough X) to 7E (grey-f.,m. sst.-flat,trough X).

There are two megacycles in this member and they contain 3D (grey-m.sst.trough X) at the base and 3C (grey-m.sst.-trough X) at the top. The vertical succession of samples in the megacycle is similar to the lateral succession on Scott Bjerg.

The section, which was continuously logged, passes upwards into the green and red sandstone members. The following sample groups occur: 3D (grey-m.sst.-trough X), 3C (grey-m.sst.-trough X), 2A (red, grey-f.,m.sst.-trough X), 2D (red-m.sst.-trough X,flat), 1D (grey-f.sst.-flat,trough X), 1B (red-f.sst.-trough X) and 1A (red-f.sst.-flat). The lowest parts of the megacycles consist of 3D (grey-m.sst.-trough X), 3C (grey-m.sst.-trough X) and 2A (red, grey-f.,m.sst.-trough X) and they pass upwards to 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X). The finer upper parts of the megacycles are red in colour. The vertical sequence is again similar to that which has been identified as a lateral sequence near the margin of a fan elsewhere. If the properties of the megacycles are considered in detail, some, such as those containing the series 1A (red-f.sst.-flat), 2D (red-m.sst.-trough X,flat), 3C (grey-m.sst.-trough X), increase in grain size and percentage of flat-bedding upwards. Some megacycles, therefore, become coarser upwards although many others become finer upwards (plate 1).

A short (70 m) section through the lower red sandstone member showed two megacycles formed by samples 2A (red, grey-f.,m.sst.-trough X), 1B (red-f.sst.-trough X), and 1A (red-f.sst.-flat). Throughout the West Rødebjerg sections 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X) are frequently associated; they are of similar fine sand but trough cross-bedding is much more abundant in 1B (red-f.sst.-trough X)

The white sandstone member consists entirely of sample groups 2A (red, grey-f.,m.sst.-trough X) and 1A (red-f.sst.-flat).

A composite sample sequence, vertically and, presumably laterally, would be:

3D (grey-m.sst.-trough X) – 3C (grey-m.sst.-trough X) – 7C (grey, red-f.,v.f.sst.-flat) – 2D (red-m.sst.-trough X,flat) – 2A (red, grey-f.,m.

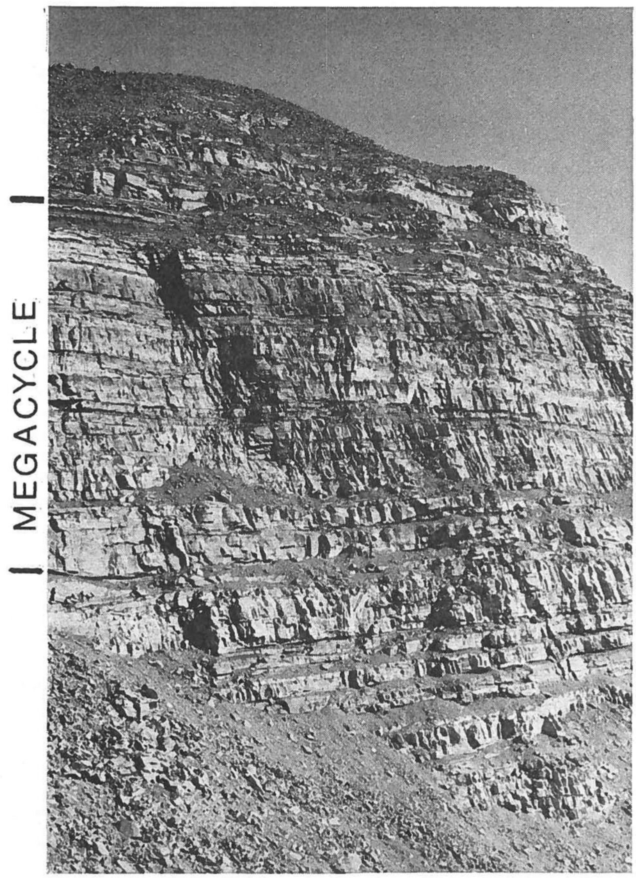

Plate 1. Cliff face on West Rødebjerg, marked to show megacycle, 25 m thick.

sst.-trough X) – 1D (grey-f.sst.-flat,trough X) – 1B (red-f.sst.-trough X) – 1A (red-f.sst.-flat).

Angelins Bjerg. On western Angelins Bjerg, green sandstones of sample groups 3C (grey-m.sst.-trough X) and 3D (grey-m.sst.-trough X) are interbedded with red sandstones of 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X). The palaeocurrent direction for the red sandstone is to the north, suggesting Rødebjerg fan, and for the green sandstone to the south-east, suggesting Scott Bjerg fan.

Sandstone in the centre of a green fan

The dominant sample group in the majority of green sandstones is 3D (grey-m.sst.-trough X) and its feldspar rich equivalent, 2C (red, grey-m.sst.-trough X), in which the major internal structure is cross-stratification. This domination is so great that some field workers have remarked that little else is seen in the Kap Kolthoff Supergroup! Some

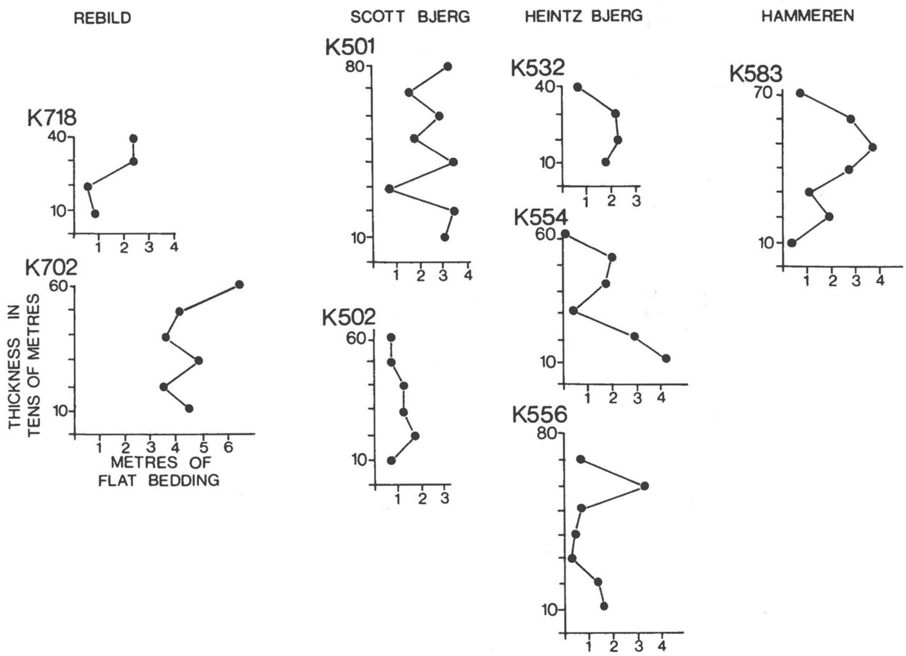

Fig. 62. Plots, for a number of different localities, showing variation in the proportion of flat bedding in 10 m samples.

plane beds are found. Fig. 62 shows graphs of the thickness of flat-bedding, in number of metres per 10 m, against stratigraphic height for a number of sections on different fans. Megacycles are clearly seen.

Megacycles, which are from 20 m to 60 m thick, were recognised in the field by the systematic variation in the amount of flat-bedding. The origin of plane beds has been discussed and we suggested that they were deposited under shallow flow conditions on the margins of channels under high power flow. We think that the increase of flat-bedding in a megacycle may be due mainly to the increase in the amount of deposition on the channel margins under flood conditions (cf Bijou Creek of McKee, Crosby & Berryhill, 1967).

The thickness of an individual cross-bedded coset is normally less than 5 m and this is the order of magnitude of the maximum thickness of sediment deposited in one event. Therefore a megacycle must consist of several events, suggesting that similar deposition must have occurred in the same place and varied systematically. The sediment may have been deposited in a gradually migrating channel complex, which existed for several flood events.

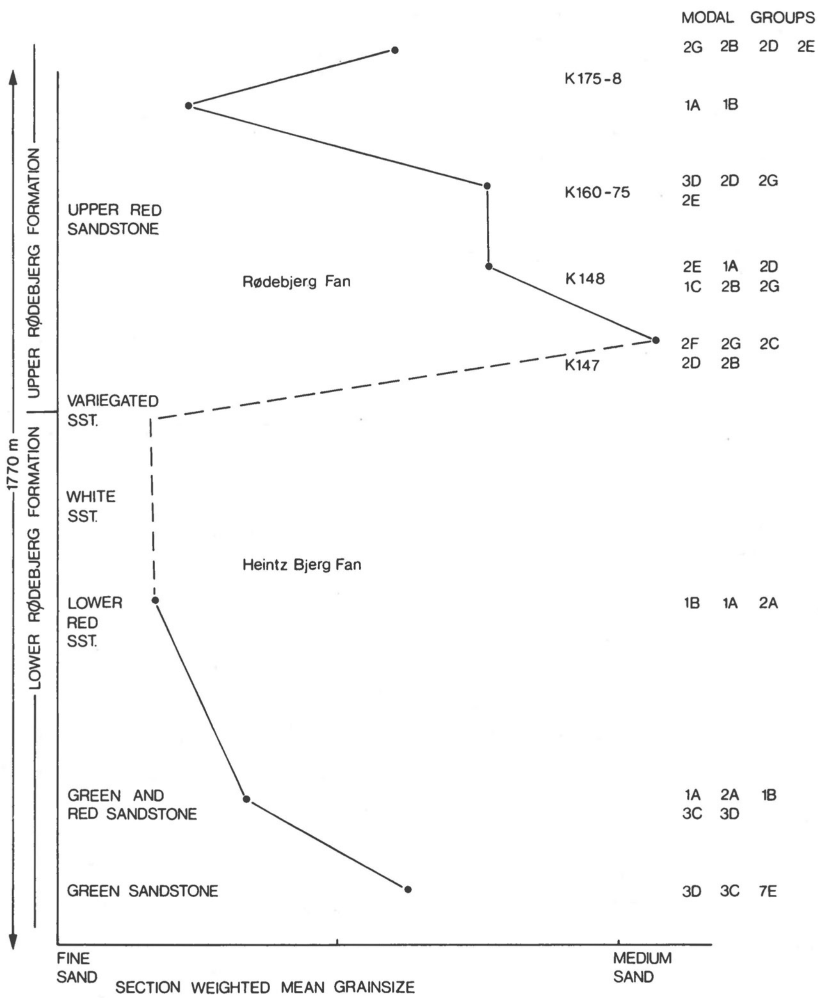

Fig. 63. Generalised succession on Rødebjerg. K numbers in the upper red sandstone member refer to parts of the section discussed in the text. Mean grain-size (weighted) for thickness of different beds) is also shown.

Red sandstone fans

Rødebjerg fan. The Rødebjerg fan is the only relatively complete red sandstone fan found by us on the Western Margin. It was examined on Rødebjerg, Svedenborgs Bjerg, Rebild and Angelins Bjerg. On Rødebjerg itself, 640 m of section was logged in the Rødebjerg fan, but it was not possible to map the lateral relationships between the samples. There are two members and these are described below.

The variegated sandstone member contains, at its base, 30 m–40 m of pebbly medium to coarse sand and belongs to sample group 3D (grey-m.sst.-trough X). Cross-stratification is very well developed. Some flat beds of fluvial origin contain occasional very coarse sand grains of quartz, which are particularly well rounded.

The succession of samples in the upper red sandstone member is very complex and a large number, such as 2B (red, grey-m.sst.-trough X), 2D (red-m.sst.-trough X,flat) and 2G (red-m.sst.-trough X,flat), are only found in the Rødebjerg fan. The section through this member (Fig. 63), which is continuous, has been divided into four arbitrary parts.

(i) K147: This was the first section recorded in the present field study and the standard of observation of the first eight 10 m units is thought to have been poor. These eight 10 m units all contain a great amount of trough cross-bedding, especially 2F (red, grey-f.,co.sst.-trough X), and above these eight there is a megacycle of 2D (red-m.sst.-trough X,flat) and 2B (red, grey-m.sst.-troguh X) which appears to be a common association.

(ii) K148: At the base there are several 10 m units of sample group 2E (red-m.sst.-trough X), which is probably a red version of 3D (grey-m.sst.-trough X), and these are overlain by five 10 m units of sample 2D (red-m.sst.-trough X,flat) interbedded with 1A (red-f.sst.-flat) and 1C (red-f.sst.-flat,trough X). 1C (red-f.sst.-flat,trough X) is similar to 2B (red, grey-m.sst.-trough X) but is modally fine rather than medium sand. 2G (red-m.sst.-trough X,flat) is also found and is a coarser version of 2D (red-m.sst.-trough X,flat), but it contains a large range of variation and probably, like sample group 7D (grey-co.sst.-trough X) is a 'dustbin' group.

(iii) K160–175: The lower part of the section is similar to K147 and K148 with a megacycle of 3D (grey-m.sst.-trough X), 2G (red-m.sst.-trough X, flat) and 2D (red-m.sst.-trough X,flat). The upper part is similar to the lower red sandstone member and the white sandstone member with 2A (red, grey-f.,m.sst.-trough X), 1B (red-f.sst.-trough X) and 1A (red-f.sst.-flat) megacycles.

(iv) K175–178: The lower part of this section is again of 1B (red-f.sst.-trough X) and 1A (red-f.sst.-flat) and in the upper portion the succession reverts to 1B (red, grey-m.sst.-trough X), 2E (red-m.sst.-trough X) and 2G (red-m.sst.-trough X,flat).

If the samples within the megacycles represent sedimentation types that occurred laterally to each other (as in the Lower Rødebjerg Formation of Rødebjerg), a sequence from the centre to the margin of the system may be deduced from the upwards transitions between them. This sequence is summarized below:

$$\mathrm{2F} \rightarrow \left.\begin{array}{r}\mathrm{3D}\\ \mathrm{2C}\\ \mathrm{2E}\end{array}\right\} \rightarrow \mathrm{2B} \rightarrow \underbrace{\mathrm{2G} \rightarrow \mathrm{2D} \rightarrow \left.\begin{array}{r}\mathrm{1C}\\ \mathrm{1D}\end{array}\right\}}_{\mathrm{2A}} \rightarrow \mathrm{1B} \rightarrow \mathrm{1A}$$

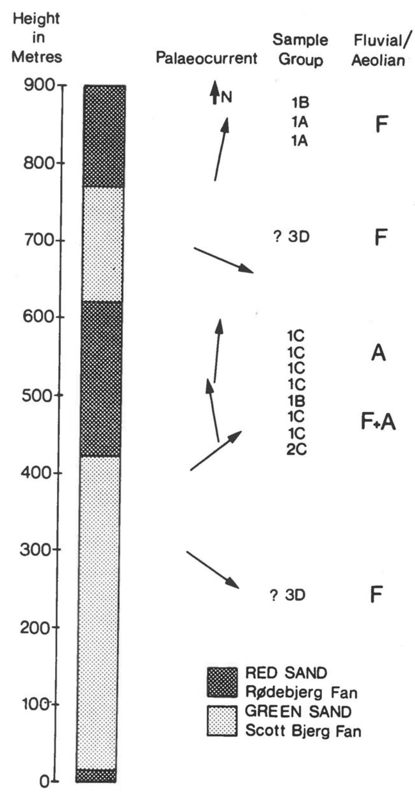

Fig. 64. Generalised succession on Angelins Bjerg, indicating red and green members, palaeocurrents, sample group classification and fluvial or aeolian interpretation.

In the Svedenborgs Bjerg red sandstone member, two associations of samples are found; 1C (red-f.sst.-flat,trough X), 2B (red, grey-m.sst.-trough X) and 2G (red-m.sst.-trough X,flat). The succession of 1C (red-f.sst.flat,trough X) will be discussed below and the association of 2G (red-m.sst.-trough X,flat) and 2B (red, grey-m.sst.-trough X) is familiar from the West Rødebjerg upper red sandstone member.

On Rebild, two megacycles are present, containing the sample groups 2D (red-m.sst.-trough X,flat) and 2G (red-m.sst.-trough X,flat). The combination of these sample groups is similar to those at the base of the West Rødebjerg upper red sandstone member.

Aeolian Deposits. Aeolian deposits were only found on the margin of the Rødebjerg red fan.

All the supposed aeolian deposits listed below consist of large trough cross-sets ranging in thickness from 1 to 4 m and in length from 5–50 m, in which channel forms could not be found. There are no intra- or extra-clasts, and brecciated laminae were found on Angelins Bjerg and in Fladedal. The following localities contain these possible aeolian deposits:

(a) Angelins Bjerg

(b) Fladedal

(c) Svedenborgs Bjerg red and white sandstone member

(d) Svedenborgs Bjerg red sandstone member

a) Fig. 64 summarizes the section on Angelins Bjerg and locates the aeolian deposits. The green sandstone members probably belong to sample groups 3C (grey-m.sst.-trough X) or 3D (grey-m.sst.-trough X), but they were not logged. The palaeocurrent direction in the green sandstone members is to the southeast, and in the red sandstone members it is to the north. This indicates that the Scott Bjerg and Rødebjerg fans are interbedded on this mountain, and that the supposed aeolian beds are near the margin of the 'red' fan.

b) The stratigraphic correlation of the Fladedal red beds with the West Rødebjerg sequence is difficult, but they are probably equivalent to the lower part of the West Rødebjerg upper red sandstone member. No aeolian beds have been recognised in the Rødebjerg succession.

The aeolian deposits of Fladedal contain sedimentary fault deformation. The basal Devonian unconformity is probably not far below this outcrop. At the top of the 15 m thick succession there is a thin conglomerate horizon. The palaeocurrent direction is to the northeast.

c) On the northwest coast of Svedenborgs Bjerg, about 20 m of red and white sandstone is exposed. The bottom 10 m belong to sample group 2G (red-m.sst.-trough X,flat) and the palaeocurrent direction is 030°. Above this are some very large (up to 4 m thick) cross-sets, with a palaeocurrent direction of 345° and the unit classifies into 2F (red, grey-f.,co.sst.-trough X). As these large sets contain no clasts, it seems highly probable that they are aeolian in origin.

In the lower part of the red sandstone member, in the Central Valley of Svedenborgs Bjerg extremely large (up to 3 m thick) trough cross-sets occur interbedded with flat sandstone units. This succession classified as sample group 1C (red-f.sst.-flat,trough X). The palaeocurrent direction is at 354°. They may be aeolian.

These two members are thought to be near the base of the Rødebjerg fan succession just overlying the Kongeborgen fan.

The geographical locations and palaeocurrents of aeolian deposits are summarized in Fig. 65. They are all near the base, or at the margin, of the Rødebjerg fan, which appears to have been fringed by aeolian sand dunes on its northern margin.

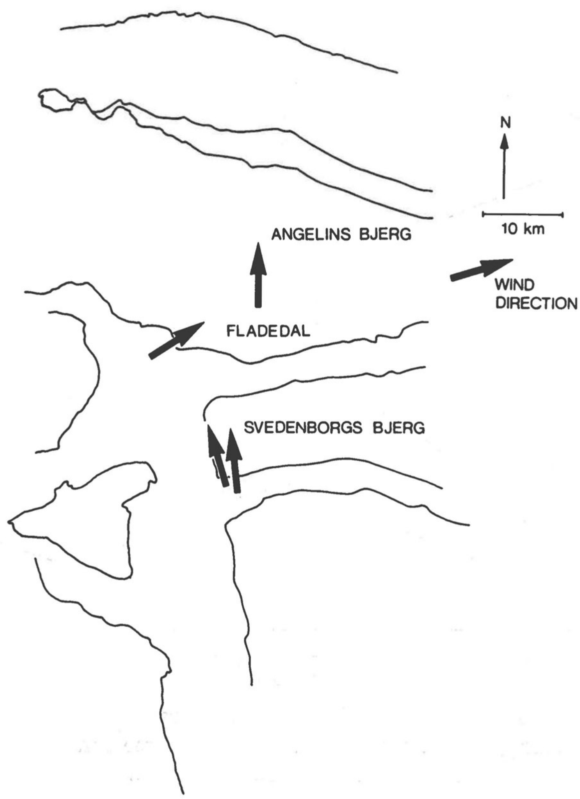

Fig. 65. Map summarising location and palaeocurrent direction of supposed aeolian deposits of the western sequence.

The northerly palaeocurrent trend is unlike that of any other deposits, and this increases the probability that these sands received a final reworking from the wind.

Possible evolution of a green fan into a red fan. A section, K504, was logged in the bottom 100 m of the Scott Bjerg red sandstone member and is illustrated in Fig. 66.

This sequence of samples is familiar from the lower parts of the Rødebjerg upper red sandstone member. The predominant internal structures are flat-bedding and trough cross-bedding and there are two green horizons in the mainly red succession. The vertical variation of these properties is illustrated in Fig. 66. Trough cross-sets up to 3.5 m thick are encountered in the next to lowest 10 m unit and these do not contain clasts. They may be aeolian in origin. The rest of the sequence is similar to deposits ascribed elsewhere to fluvial deposition.

The underlying Scott Bjerg green sandstone member consists almost entirely of sample group 3D (grey-m.sst.-trough X) and the red sandstone

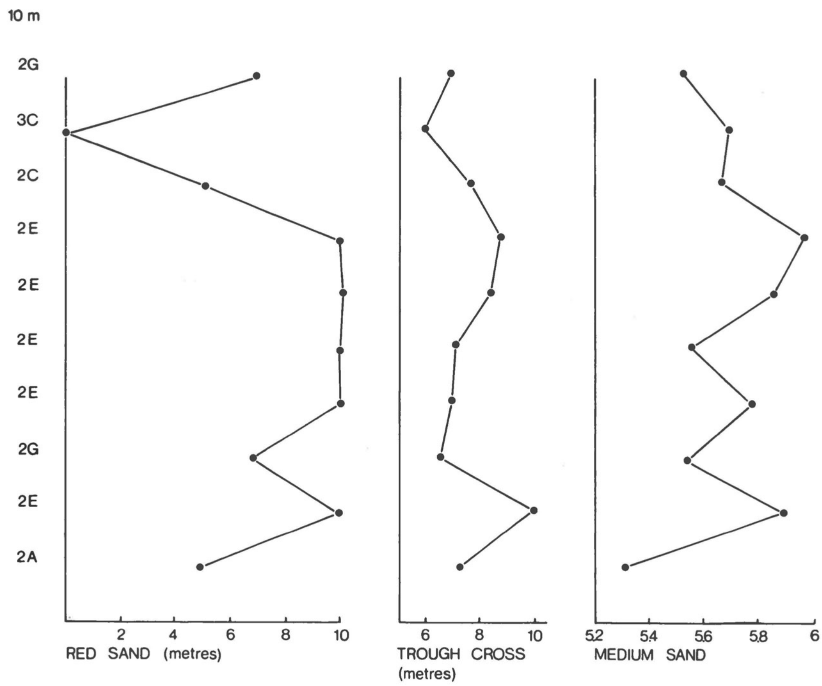

Fig. 66. Succession logged at K504 in Scott Bjerg red sandstone member. Classification of 10 m samples is shown with proportions of red sandstone, cross-bedding and medium-grained sandstone.

member may be similar except for colour. To test this, all 10 m samples in the red sandstone member were reclassified, assuming that they were entirely green and the following succession was obtained:

(10 m samples)

3C
3C
3D
3D
3D
3C
3D
3C
3D
3A

There is considerably more variation in this artificial sequence than in the Scott Bjerg green sandstone member.

The red sandstone member is at approximately the same stratigraphic level as the Angelins Bjerg red sandstone and Rødebjerg upper red sandstone members and so it is possible that they are all part of the same fan system. However the palaeocurrent direction for the Scott Bjerg red sandstone member is 090°, which is similar to the Scott Bjerg green sandstone member and almost at right angles to the direction in the Angelins Bjerg red sandstone members. The red facies on Angelins Bjerg are mainly 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X), which have been deduced to be marginal deposits whereas the red samples on Scott Bjerg are typical of deposits nearer the centre of a fan. It seems unlikely that the Scott Bjerg red sandstone member is part of the Rødebjerg fan. We suggest that it formed during a late stage in the development of the Scott Bjerg fan in which the environment became similar to that of the lower Rødebjerg fan.

Fan migration with time

Scott Bjerg, southern margin. The weighted mean grain size of each member decreases upwards in the Scott Bjerg fan on West Rødebjerg (Fig. 63).

A vertical decrease in mean grain size might be caused by:

(a) decrease in grain size supplied to the system
(b) decrease in transport power of river
(c) decrease in time during which the flow power exceeded critical values
(d) the location becoming relatively more distal in the fan system
(e) lateral movement of the fan

Because the grain size in the Lower Rødebjerg Formation on Scott Bjerg itself does not decrease upwards, the first four mechanisms may be rejected. The overall vertical sequence of sample groups in the Lower Rødebjerg Formation on West Rødebjerg is similar to that found elsewhere laterally at the margin of a green sandstone fan. The vertical succession can be explained, therefore, by the lateral migration of the entire fan.

Kongeborgen fan, northern margin. The Svedenborgs Bjerg green sandstone Member wedges out to the north, the upper part of the member being further north than the lower. This shows that the Kongeborgen fan migrated northwards. The Kongeborgen fan was contemporaneous with the Scott Bjerg fan of the Lower Rødebjerg Formation on West Rødebjerg. Therefore, both fans were migrating at the same time. One can conjecture that the development of the Kongeborgen fan forced the major flow of the Scott Bjerg fan to the north and left the area of 'marginal deposits', already described, between them. The evidence for this area is the occurrence of red very fine sand samples, 5A (red-v.f.sst.-flat,asym.rip.) to the north of the Kongeborgen fan on Svedenborgs

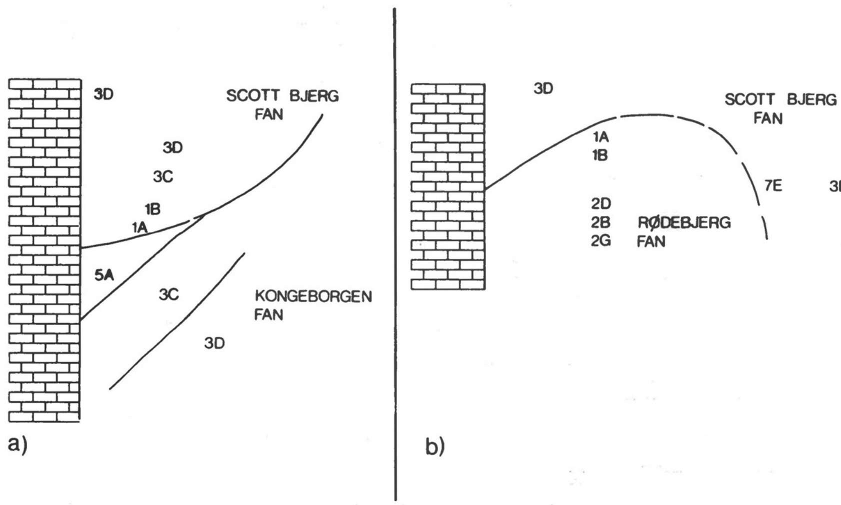

Fig. 67. Sketch map illustrating fan margin relations: a) Lower Rødebjerg Formation times, showing sample groups of inter-fan area between Scott Bjerg and Kongeborgen fans, b) Upper Rødebjerg Formation times, showing relationships between sample groups of Scott Bjerg and Rødebjerg fans.

Bjerg. Sample groups 3C (grey-m.sst.-trough X) and 3D (grey-m.sst.-trough X) occur interbedded in these red samples but no further than 100 m–200 m from the main mass of the Svedenborgs Bjerg green sandstone member, which suggest that there was some restraint on the Kongeborgen fan. The Scott Bjerg fan may have been this restraint (Fig. 67a).

Rødebjerg fan, northern margin. The weighted mean grain size and amount of trough cross-bedding for five subdivisions of the Rødebjerg fan on Rødebjerg both decrease upwards (Fig. 63). The sample groups change at the same time from those typical of the centre of the fan, 3D (grey-m.sst.-trough X) and 2E (red-m.sst.-trough X) to those of the margin, 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X). South of Rebild the red sandstone member wedges out to the south, the upper part of the member being furthest south. This suggests that the Rødebjerg fan migrated to the south.

The sample groups at the margin of the fan are shown in Fig. 67b.

Typical fans and their environments (Table 10)

Green fans

Volumetrically a high proportion of each of the green fan deposits belongs to sample group 3D (grey-m.sst.-trough X) or to its red and green equivalent 2C (red, grey-m.sst.-trough X). Other sample groups

Table 10. *Comparison ofprobable hydrology and and lithology, or red and green fans and conglomerate environments*

	Red fan	Green fan Centre	Green fan Margin	Conglomerate
Peak dischange in tributaries	low	high	?	high
Width of peak discharge	narrow	wide	?	narrow
Limestone Clasts	none	sometimes	rare	common
Silt in lenses	common	never	common	sometimes
In situ calcareous concretions	common	never	never	?
Plant roots	common	never	rare (?)	
Tubes	common	never	rare (?)	
Colour	RED	GREEN	RED	RED

only occur at the margins of the fans, either near the unconformity (eg. Scott Bjerg) or between two fans (eg. Svedenborgs Bjerg.)

Where the marginal deposits of a sandstone fan occur in contact with a major conglomerate body, it is interesting to consider whether the fine-grained marginal sediment was derived from the sandstone fan or from the conglomerate. Certainly all our work on the multivariate analysis of sediment types from fan centre to margin has shown that there is a complete and gradual transition from fan centre to the fine-grained marginal type. But this merely tells us that environments of sedimentation merged laterally into each other. It does not tell us about the derivation of the fine-grained material. Important evidence comes from Syltoppene and Hammeren where the red very fine-grained sand is associated with conglomerate in valleys. It seems very unlikely that green sand material penetrated these valleys at all. In these cases then, we can assert that the red fine-grained material was derived from conglomeratic fluvial systems.

Conditions suitable for the formation and preservation of samples from groups other than 3D (grey-m.sst.-trough X) and 2C (red, grey-m. sst.-trough X), occur only at the margins of fans. We suggest that the special conditions were the presence of long lasting morphological features (hills of basement, or fans of gravel) that influenced the "normal alluvial sedimentation" of the green sandstone rivers. Fig. 68 illustrates our idea.

The junction between the 'normal' green sand, and the marginal red sediments is often very sharp. For example, on Svedenborgs Bjerg the red facies are interbedded with green facies in the zone only about

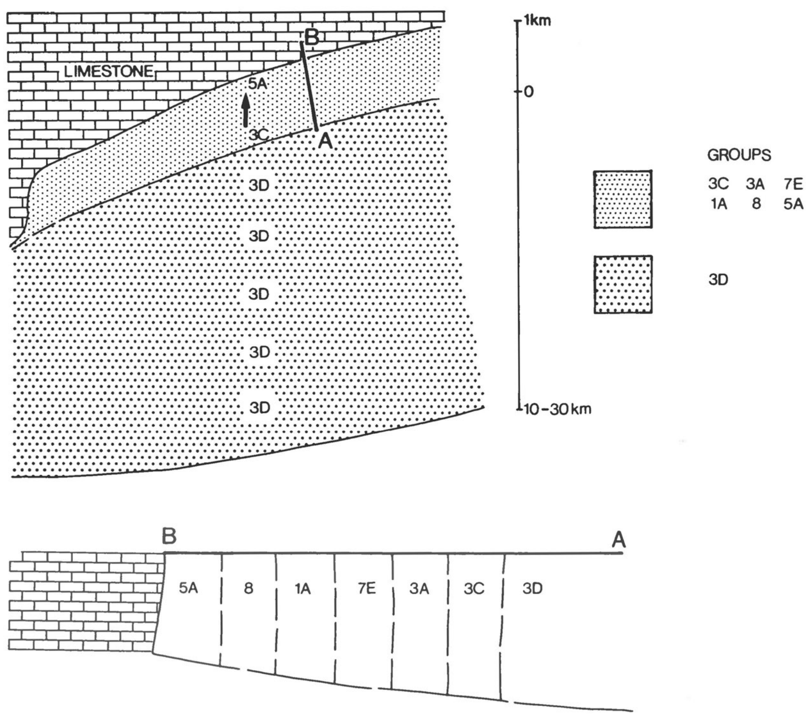

Fig. 68. Sketch map and vertical plane section illustrating sample group relationships generalised for the margin of an alluvial fan. The characteristically marginal sample groups are typically developed in an embayment of the basement of pre-Devonian limestones.

100 m wide. The junction on Scott Bjerg is equally sharp and continues in a similar location through a vertical thickness of approximately 600 m. These two observations confirm the presence of an inerodable feature restraining the main channel.

The fine sediments were probably deposited by floods (McKEE et al, 1967). A stream tends to flow along a course with maximum gradient, and therefore minimum curvature (COLEMAN, 1969 p. 168). If the channel was flowing next to an inerodable bluff, it would follow the path shown in Fig. 69, and not flow across the area A. Thus any sediment deposited in this area would not be liable to erosion by the main channel, and would be deposited by less powerful flows.

In the discussion of modern flood deposits in Bijou Creek (McKEE et al, 1967), it was shown that medium grained sand was trapped in the talweg whilst fine sands were deposited in the upper flow regime on the flood plain. There must have been a similar situation at the margins of these 'green sand fans', as the power required to transport very fine sand at the flat bed-asymmetrical ripples transition (which is common in

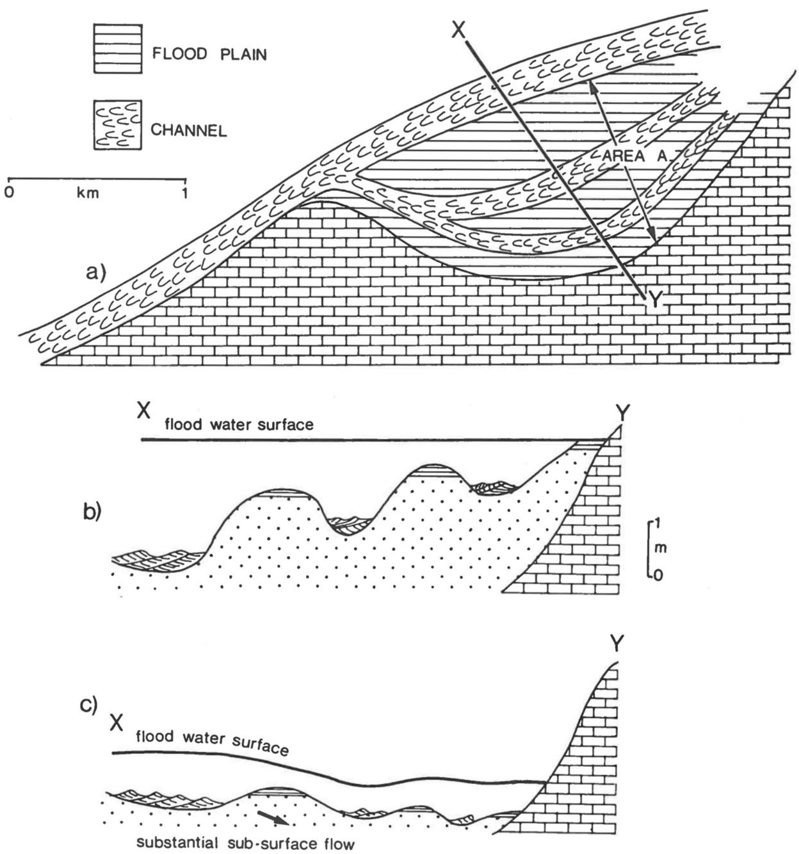

Fig. 69. Sketch map (a) and sections (b and c) illustrating possible situations on fan margins. Pre-Devonian limestone basement is shown by a brick symbol. Sections b and c illustrate two alternatives, in the second of which substantial water flow percolated into the alluvium.

sample group 5A (red-v.f.sst.flat,asym.rip.), at the extreme margin of the fan, is similar to that required to move medium sand in the dune phase (Guy et al, 1966).

The grain size sorting may have been the result of the mechanism suggested by Allen for point bars (Allen, 1970). The flow pattern in the main flood channel probably had some lateral component at an angle to the flood direction and this component of flow transported the sediment up the bank of the channel. Gravity, acting down the slope, was balanced by decreasing flow up the slope, and this stopped coarser particles passing on to the floodplain. The power in the direction of the flood was still sufficient to move the sediment in the upper flow regime.

The presence of trough cross cosets in samples nearer the margin of the fan than sample group 3D (grey-m.sst.-trough X), suggests that there were many channels, and the decrease in setsize suggests that they were shallower nearer the side. The palaeocurrents in all trough cross-bedding regardless of the sample group are approximately parallel suggesting that the smaller lateral channels were sub-parallel to the main channel. The transport power in these smaller channels was probably less than in the larger ones and so the sediment that reached the margin of the fan was sorted several times and only the finest particles reached the edge.

As was described above, the centre of the fans consisted of only sample group 3D (grey-m.sst.-trough X) in megacycles of up to 60 m thick. It was also suggested, in that section, that the majority of the flat-bedding, which is most abundant at the top of the megacycle, was formed as a flood deposit. The grain size of the flat beds is finer than that of the trough cross-bedding and this suggests that medium sand was trapped in the talweg during the high stage of the flood.

Megacycles near the margin of the fan consist of samples from several groups, those with the most trough cross-bedding have been shown to be nearest the centre of the fan and those with the least nearest the margin. If this idea is applied to megacycles in the centre of the fan, then the part of the megacycle with the most flood plain deposits was nearest the margin of the fan, and that with the most channel deposits nearest the centre (Fig. 70).

It is not possible to measure in the field the width of these channel complexes. But the channel complex of the Brahmaputra, which is on a much larger fan than these Greenland fans, is 2–6 miles wide (COLEMAN, 1969, p. 148).

It was also shown, above, that the megacycle was a composite feature made up of several flood events. Therefore the channel complex must have been a relatively longer lived feature which steadily migrated across the fan surface for a considerable period of time. The initiation of a new megacycle may have been a response to a tectonic movement in the basin or in the source area, to avulsion of the channel on the fan, or climatic change. It is not possible to distinguish between these origins.

No fine beds are found in samples from group 3D (grey-m.sst.-trough X). The presence of abundant mudflakes, plant fragments, and intraformational limestone clasts suggests that fine sediment was deposited at the margin of the channel complex but was always removed by erosion. This apparently occurs in the present day Brahmaputra (COLEMAN, 1969, p. 232) where the fine-grained deposits are very thin, less than 2.5 cm.

The Brahmaputra is bounded by levées (ibid p. 230) and the presence of these in the centre of Gjeenland fans may have restricted the occurrence of sample groups such as 3C (grey-m.sst.-trough X), 7E (grey-

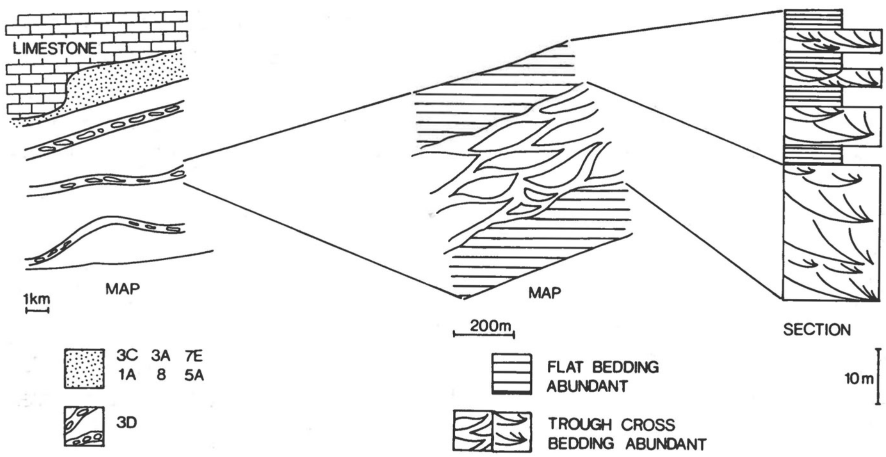

Fig. 70. Sketch maps and section, illustrating hypothesis to explain megacycles in fan sedimentation.

f.,m.sst.-flat,trough X) and 3A (grey-f.,m.sst.-trough X). No other evidence for levées has been found however.

Coarser sandstone margins of fans have only been found where two fans appear to have been close to each other. The best example is in the Scott Bjerg fan of the Lower Rødebjerg Formation on Rødebjerg itself. The trends of grain size and colour from the centre of the fan to the margin are similar to those seen in very fine sand margins, but the marginal samples are of groups 1A (red-f.sst.-flat) and 1B (red-f.sst.-trough X).

The distance between the Scott Bjerg and the Kongeborgen fans is about 5 km at the point where we made our study on Rødebjerg. The place of actual contact of the two fans may have been 10–15 km to the east. This suggests that the area of restricted flow was very large compared with that at the margin of Scott Bjerg, near the unconformity, where the area of restricted flow was probably about $^1/_2$ km by 2 km. The lowest alluvial gradients, and therefore the very-fine sand sedimentation, may have been features of small and local topographic hollows, and not of larger hollows such as this one.

Red fans

The only clear example of a red fan is the Rødebjerg fan. It differs from green fans in three ways:

a) it is red

b) flat beds are much more abundant. If the colour of the rocks is ignored, sediments with grain size and structure similar to the common

3D (grey-m.sst.-trough X) are not common. Most of the sediments classify, if their colour is changed, as 3C (grey-m.sst.-trough X) or 7E (grey-f.,m.sst.-flat,trough X) and 3A (grey-f.,m.sst.trough X). We suggest that the flat-bedding was probably formed by flows that were insufficiently long-lived or deep to allow the formation of megaripples (and therefore cross-bedding).

c) lenses of asymmetrical ripples are common, often occurring above cosets of cross-stratification. The lenses are often cut by rootlets and tubes, and concretions are also common. These lenses have not been found on any of the green fans, their position usually being occupied by flat-bedded sediments in the green situation. We suggest that these ripple-fllled lenses were probably formed in minor channels that were characterised by relatively gentle flow. In contrast the flat-bedding of the green fans implies stronger flow. The concretions suggest a well-drained location above the mean annual water table (BÜTLER, 1958).

These structural features characteristic of the red fan, combine to suggest that it accumulated from flows that were relatively short-lived and gentle, compared with those of the green fans or the Sofia Sund system.

In work on other Old Red Sandstone basins, FRIEND (1966) suggested that the level of the ground water in sediments after their sedimentation exerted an important influence on their ultimate colour, by controlling the reduction of ferric oxides in the sediments. Our consideration of the environment of the red fan has just shown that it may have been especially well drained. The same may also have been true of the margins of our green fans that are now characterised by pockets of red sediment, but it is rather more difficult to see why these pockets chould be particularly well-drained.

Another way of explaining the distribution of redness in the Greenland Devonian is based on the idea that it is largely determined by differences of permeability after sedimentation. Thus the rather coarser, and more cross-bedded green fan sediments may have been reduced by passage of reducing groundwater, leaving the finer-grained, less cross-bedded red fan, and the pockets of fine-grained marginal sediment, to become red.

The other common occurrence of redness in the Greenland sequence, is in the marginal and basal conglomerate bodies. Here their marginal position, and their high porosity would have led to high water throughflow. Under these conditions rapid diagenesis in oxidising waters could have led to general redness.

Table 11. *List of stratigraphic terms, western sequence*
(only formal units are listed here; numbers indicate stratigraphic sequence and hierarchy)

1. Kap Kolthoff Supergroup	1.1	Lower Rødebjerg Formation
		Ella Ø Conglomerate Member
	1.2	Upper Rødebjerg Formation
	1.3	Sofia Sund Formation
2. Kap Graah Group (no formal subdivisions)		

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